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EVALUATION OF COVERALL MATERIALS FOR PYROTECHNIC OPERATIONS

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US ARMY ARMAMENT MUNITIONS & CHEMICAL COMMAND
ARMAMENT RDE CENTER

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This project was accomplished as part of the U.S. Army's Manufacturing Methods and Technology Program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tests were performed on six different materials used for operator coveralls for pyrotechnic applications. Included in these materials were Nomex and 100% fire retardant cotton. Two types of tests were performed, thermal and static electricity discharge. In the thermal tests, samples of materials were instrumented with thermocouples and subjected to fires involving typical quantities of pyrotechnics. The electrical discharge consisted of charging

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20. ABSTRACT

material samples and measuring the time required to dissipate 50% of the charge (i.e., the half-life). The data were recorded and analyzed, and conclusions and recommendations were made.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Harry Winer of the Navy Clothing and Textile Research Facility for his assistance in the selection of the coverall materials, for providing samples of the materials, and for laundering the test materials. The authors would also like to thank M. Ray Burgamy and Steven W. Olson of Southwest Research Institute for their assistance in conducting the thermal tests on the coverall materials and the Hazards Research Corporation for their participation in conducting the electrostatic discharge tests.

CONTENTS

FIGURES

INTRODUCTION

A possible cause of a number of pyrotechnic incidents occurring after the mixing/granulating operations and before pack-out is the ignition of a composition from electrostatic buildup and discharge from an operator's coveralls. The currently used coverall materials are susceptible to electrostatic buildup, and thus the potential for an ignition. Other materials are available which reduce/eliminate electrostatic buildup and still provide the same degree of protection. In addition to the risk of electrostatic buildup, some materials are better thermal insulators than others and would provide a higher level of protection to an operator should a fire result.

This program was designed to evaluate both the currently used coverall materials and the new materials being developed to determine which materials provide the higher levels of thermal protection and at the same time are least likely to develop and hold a static charge. This report summarizes the work performed in selecting the six candidate coverall materials, the thermal tests performed by Southwest Research Institute, and the electrostatic sensitivity tests performed by Hazards Research Corp., for SwRI. Included in this report are conclusions and recommendations.

COVERALL MATERIAL SELECTION

The materials for electrostatic and thermal testing were selected by ARDC based on their usage in the pyrotechnic manufacturing plants and on their availability. The purpose of the test program was to evaluate the materials being used in the field and also any materials being developed for use in protective clothing. In selecting these materials, input was solicited by ARDC from SwRI, Hazards Research Corp., personnel, and from Mr. Harry Winer of the Navy Clothing and Textile Research Facility. Initially, a list of eight materials was developed as shown in Table 1, and six materials were selected from the eight. These materials are typical of what is currently in use or are being developed as flame retardant fabrics. The material weights are as currently manufactured and this program did not take into consideration the effect of fabric weight on the thermal insulation or electrostatic charge dissipation properties. The electrostatic discharge tests were performed on the materials in two conditions, unlaundered and after 25 washings and dryings.

Table 1. Candidate Coverall Materials

Material No.	Material
*1.	Nomex®/S.S. (99/1)
*2.	100% Fire Retardant Woven Cotton 8oz.
3.	100% Fire Retardant Knit Cotton 8oz.
*4.	20/80 PBI/Nomex® 1, 4.9oz.
*5.	35/35/30 PBI/Kevlar®/Durvil® 7.5oz.
*6.	40/60 PBI/Kevlar® 4.5oz.
7.	20/80 PBI/PFR Rayon 4.4oz.
*8.	20/80 PBI/PFR Rayon 7.2oz.

Note: * Materials Selected For Testing

THERMAL TEST PROGRAM

Test Procedure

The testing of the six coverall materials was conducted at the SwRI test facility. As shown in Table 1, the six materials tested were: No.1, Nomex®/stainless steel(99/1); No.2, 100% fire retardant woven cotton; No.4, PBI/Nomex® 1 (20/80); No.5, PBI/Kevlar®/Durvil® (35/35/30); No.6, PBI/Kevlar® (40/60); and No.8, PBI/PFR Rayon (20/80). Tests were performed using two types of material layers, single and double (the double layer was tested to simulate pockets and overlaps on the coveralls where two layers of the material would be present) and using a range of pyrotechnic weights (20,40,80,160,320, and 454 grams). Two different pyrotechnic materials were used, an aluminum base starter mix and a magnesium base illuminating mix (M206). A skin simulant thermocouple manufactured for SwRI by Albany International Research in Dedham, Massachusetts, and two thin bare wire thermocouples were used to measure temperatures for each material. One of the thin thermocouples was placed directly in back of the material to record the gas temperature as it passed through the material, and the second thin thermocouple was punched through the weave of the material (see figure 1) to measure the flame and gas temperature on the surface of the material. The skin simulant was mounted flush on a wooden board (see figure 2) and measured the temperature rise through the materials covering the board. The six materials (single or double layers) were each attached to wooden boards and mounted symmetrically around the simulated mix muller as shown in figure 3. The pyrotechnic was placed in an open container as shown in figure 4 and was located 18 in. from the material test specimens. The pyrotechnic was ignited remotely at the top of the mix, and the thermocouple data were recorded real time on analog tape and then played back and analyzed. Prior to each test, each material was visually checked for burn holes or degradation and replaced as necessary.

Test Results

Starter Mix Tests

On the tests performed using the aluminum-based starter mix, it was observed that measurable damage to the materials did not occur until the larger pyrotechnic weights were used,i.e., the 320 gram tests and the 454 gram tests. Figures 5 and 6 show the overall view of the single layer materials and the double layer materials following the 454 gram test. As shown in these figures, the damage consists primarily of burn holes where the burning pyrotechnic struck the material. No catastrophic damage such as complete combustion or melting was observed; however, it should be noted that the maximum quantity of pyrotechnic used was relatively small. As previously mentioned, the temperature data were recorded real time on analog tape and preliminary analyses have been conducted. Figure 7 presents the maximum temperature rise measured by the skin simulants mounted behind each of the six

test materials (Mat'l no's. 1,2,4,5,6,8) as a function of pyrotechnic weight for the single layer tests. Figures 8 and 9 present similar data for the exposed thermocouples (the ones through the material weave), and for the covered thermocouples (the ones directly behind the material). Figure 10 presents the maximum temperature rise recorded by each of the material skin simulants as a function of the average temperature recorded by the corresponding exposed thermocouples. Figures 7 and 10 can be used to evaluate the various coverall materials effectiveness as a thermal insulator. In both figures, the skin simulant behind material no. 2,(the 100% fire retardant cotton) measured lower temperatures than did any of the other material skin simulants. Conversely, the skin simulant behind material no. 6 (the PBI/Kevlar® 40/60), measured the higher temperatures of all skin simulants. This would imply that the 100% fire retardant cotton is the best thermal insulator of the six materials tested with the given weights of the pyrotechnic starter mix.

A similar test program and subsequent analyses were performed using double layers of the candidate coverall materials. Figures 11, 12, and 13 present the maximum temperature rise for the skin simulants, the exposed thermocouples, and the covered thermocouples, respectively, as functions of the pyrotechnic weight. Figure 14 presents the maximum skin simulant temperatures for each of the six materials as a function of the average temperature measured by the corresponding exposed thermocouples. As shown in figures 11 and 14, the skin simulant behind material no. 2 (the 100% fire retardant cotton) measured the lowest temperature of the thermocouples. Similarly, the skin simulant behind material no. 6 measured the higher temperatures of the thermocouples. If the test results of the single layer tests are compared to the results of the double layer tests, one will see that as expected, the skin simulants behind the double layers saw less of temperature rise than did the skin simulants behind the single layers of the materials. In both the single and the double layer tests, the 100% fire retardant cotton appeared to be the best thermal protector, while the PBI/Kevlar® appeared to be the worst thermal protector.

M206 Mix Tests

The testing of the six coverall materials (both the single layer and the double layer) using the dry M206 mix was performed using the same test procedures as used on the starter mix tests. For the tests involving the single material layers, Figure 15 presents a curve of skin simulant temperature rise versus pyrotechnic charge weight for the six materials tested. Figures 16 and 17 present the exposed and the covered thermocouple responses versus charge weight, respectively. Figure 18 presents the skin simulant temperature rise as a function of the average exposed thermocouple temperature. As can be seen in figure 15, the worst materials (those that passed the largest amount of heat) are materials 2 and 4. The best materials (those exhibiting the lower temperature rise) are materials 8, 1, 5 and 6. It should be noted that the temperature differences between materials 8, 1, 5 and

6 are not that large and actually only 14 degrees separate these four materials. If a comparison is made between the results of the single layer tests involving the starter mix and the tests with the M206 mix (see Figure 19) one will see that in the starter mix tests, material no. 2 is the best or lowest temperature material, while in the larger quantity M206 tests (320 gram and 454 gram), material no. 2 is the worst or highest temperature material. One possible reason for this change in performance could be that in the larger quantity tests, the M206 fire is such a severe fire that material no. 2 breaks down completely and loses its insulating capacity. If one looks at the lower quantity tests involving the M206, one will see that the material no. 2 exhibits fairly good insulating properties not unlike any of the other "better" materials and it is only at the higher quantities that the material breaks down. Inspections of the materials after the larger quantity tests using the M206 revealed that the materials suffered severe burns and actual physical degradation and failure. Figures 20 and 21 present post-test conditions for the six materials for the 320 gram test and for the 454 gram test. As shown in these photographs, the materials' position starting from right to left is material no. 1, 2, 4, 5, 6, and 8; and as can be seen, all of the materials have been substantially damaged, in particular material no. 2. Figures 22 and 23 are closeups of the two tests with emphasis on material no.2 and, as can be seen, material no. 2 has suffered damaging burns and has actually split down the center. At the same time, material no.'s 5 and 8, which also suffered severe burns, exhibited very good insulating capabilities and had the lower skin simulant temperatures in both sets of tests.

The tests performed using the M206 and the double layers of materials have also been evaluated and the results are presented in Figures 24-27. Figure 24 presents the skin simulant temperature rise as a function of the pyrotechnic charge weight, while figures 25 and 26 present the exposed and the covered thermocouple temperatures also as a function of charge weight. Figure 27 shows the skin simulant temperature rise as a function of the average exposed thermocouple temperature. Once again, materials 2 and 4 exhibited the larger skin simulant temperature rise, but as can be seen in Figure 24, these materials do not exhibit extraordinary high temperatures until the 320 gram and the 454 gram tests which was the same phenomenon seen in the single layer tests. Materials 1, 5, 6, and 8 again measured the lower skin simulant temperatures indicative of their insulating capability. Figures 28 and 29 show the six materials following the 320 gram and the 454 gram tests, and as shown, the materials, primarily no. 2, sustained severe burns and physical degradation.

ELECTROSTATIC DISCHARGE TESTS

A number of electrostatic charge relaxation tests were performed on the six selected coverall materials by Hazards Research Corp., as a subcontractor to Southwest Research Institute. Details of the test setup, the test procedure, and the test results are provided in the report prepared by Hazards Research Corp., which is included in this report as Appendix 1. However, for completeness, a brief description of this phase of the program is included in the following paragraphs.

The test procedure used was standard test method ASTM D-2679-73 and consisted of charging a sample of the coverall material with a known charge and then releasing the charged sample into a Faraday Cage and measuring the time required for the material to dissipate 50% of the charge, i.e., the charge half-life. Two tests were performed on each of five samples of each coverall material for a total of 60 tests. The coverall material samples were then shipped to the Navy Clothing and Textile Research Facility where they were laundered 25 times simulating normal use. The laundered materials were then retested to see what effect laundering might have on the ability of the materials to hold a charge.

The tests conducted on the materials yielded some key results including the following: the PBI/Kevlar®/Durvil® material dissipates the static charge faster than any of the other five materials both in the unlaundered and laundered conditions, and the laundering of the materials increased the charge relaxation time for all of the materials and the magnitude of the increase varied significantly between materials. Details on these and other test results and additional conclusions can be found in the appendix.

CONCLUSIONS

Based on the thermal tests performed on the six candidate coverall material tests, the following conclusions have been formulated:

* The resultant fire from ignition of 0.45 kg (1 lb) of starter mix is not severe enough to cause any physical damage to the coverall materials. The M206 fires are very severe fires and above 160 grams, all of the candidate coverall materials suffered severe damage.

* On the starter mix tests, the materials exhibiting the best thermal insulating properties are the following (in decreasing order): 100% fire retardant woven cotton; PBI/Kevlar®/Durvil® (35/35/30); PBI/PFR Rayon (20/80); PBI/Kevlar® (40/60); Nomex® S.S.; and PBI/Nomex® (20/80).

* On the M206 tests, the materials exhibiting the best thermal insulating properties are the following (in decreasing order): PBI/PFR Rayon (20/80); Nomex® S.S. (99/1); PBI/Kevlar®/Durvil® (35/35/30); PBI/Kevlar® (40/60); PBI/Nomex® (20/80); and 100% Fire Retardant Cotton.

* Electrostatic charge relaxation experiments conducted on six flame-retardant fabrics before and after laundering provided a means of rating the materials based on the fastest dissipation of the induced static charge. Using the half-life technique, the following is a list of the materials in the order from the fastest to the slowest electrostatic charge dissipator before and after laundering. (Although laundering in general appeared to increase the charge dissipation, the magnitude of the effect differed between fabrics as noted on the material ratings.)

	Before Laundering	After Laundering
1.	PBI/Kevlar®/Durvil®	PBI/Kevlar®/Durvil®
2.	PBI/Kevlar®	PBI/Nomex® I
3.	PBI/PFR Rayon	PBI/PFR Rayon
4.	Nomex®/SST	PBI/Kevlar®
5.	Woven Cotton	Woven Cotton
6.	PBI/Nomex® I	Nomex®/SST

RECOMMENDATIONS

The following recommendations have been developed based on the results and observations of this program.

* Since the PBI/Kevlar®/Durvil® is one of the better thermal insulators and is also the best material for dissipating static electricity, it is recommended that this material be used for protective clothing.

* For those processes where the operators are handling M206 pyrotechnic quantities of 320 grams or larger, it is recommended that the operators not wear coveralls made out of Nomex®/S.S. or 100% Fire Retardant Cotton due to the observed physical decomposition of these two materials under high heat loads.

* It is recommended that gloves or other hand protection worn by operators be evaluated experimentally using the more severe fire environment produced by the M206 to determine the level of protection given the operators hands. It was observed in the tests performed by SwRI that some materials will shrink and crack under high heat loads and the gloves currently being used should be tested to insure that these physical breakdowns do not occur.

* One of the tests involving 0.454 kg of M206 mix, a standard plastic faceshield used in grinding operations, was placed above the material samples at a height simulating the operator's face. The subsequent ignition of the M206 totally destroyed the faceshield and would have provided no protection for the operator. It is recommended that the faceshields used in the processing of the M206 mix be evaluated experimentally against typical quantities of M206 to determine what level of protection they provide.

* Based on the results of this program, it is recommended tha operators wear loose-fitting thermal protective clothing instead of tight-fitting clothing. Loose fitting clothing will provide an air space between the operator and the clothing itself and this air space will in turn serve as an insulator. In addition, a small amount of material shrinkage will not have an adverse affect on the operator.

* Since it was demonstrated that the double layers of material provide a higher level of thermal protection, it is recommended that operators wear thermal protective clothing made up of multiple layers of the better thermal insulating materials.

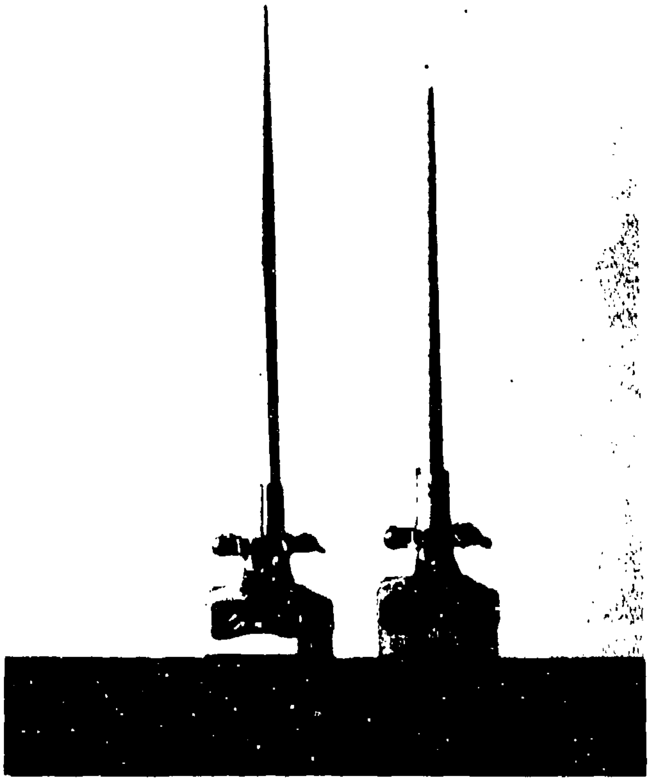


Figure 1. Thin Wire Thermocouples

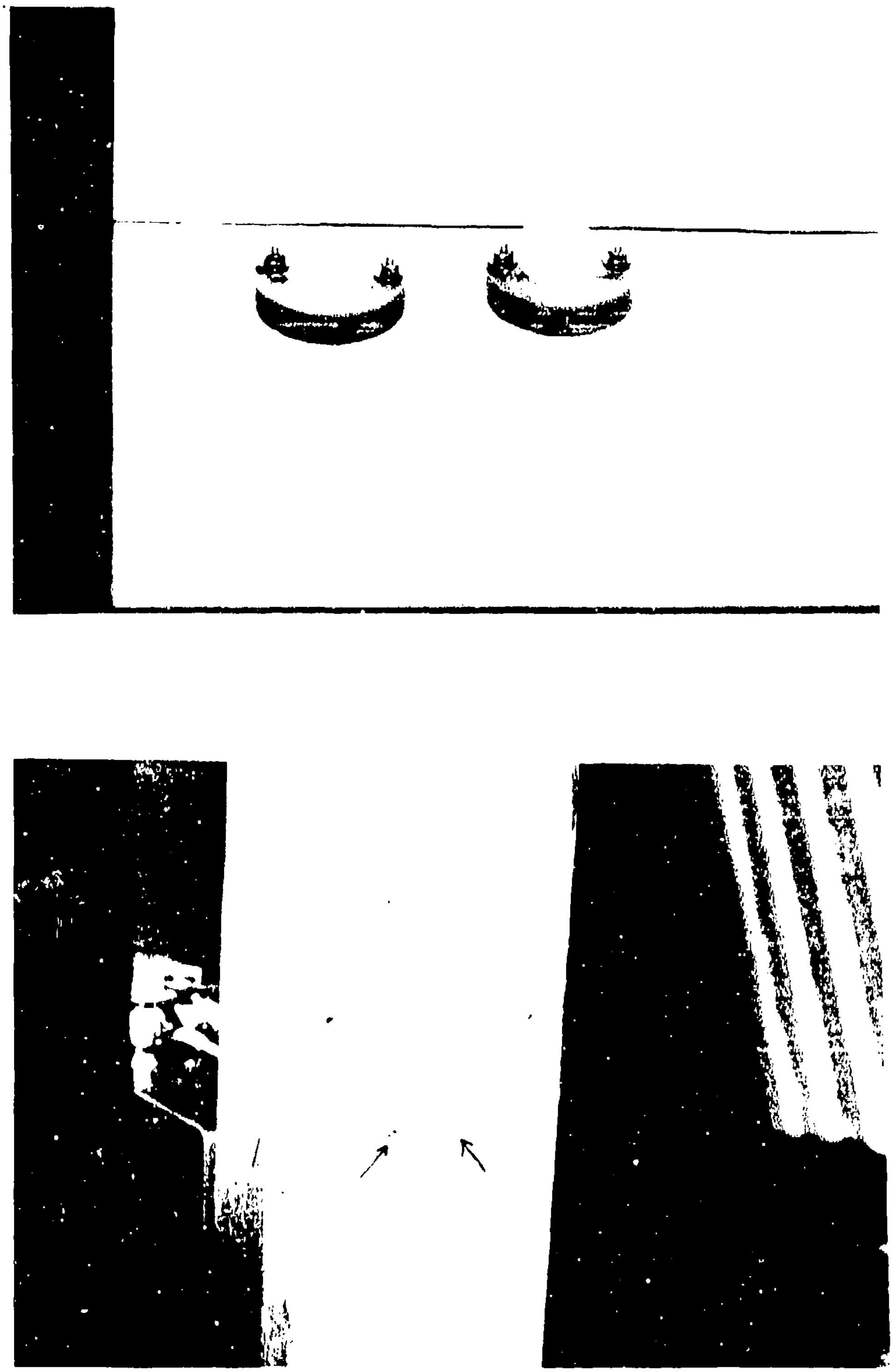


Figure 2. Thin Thermocouples and Skin Simulants Mounted in Wooden Post

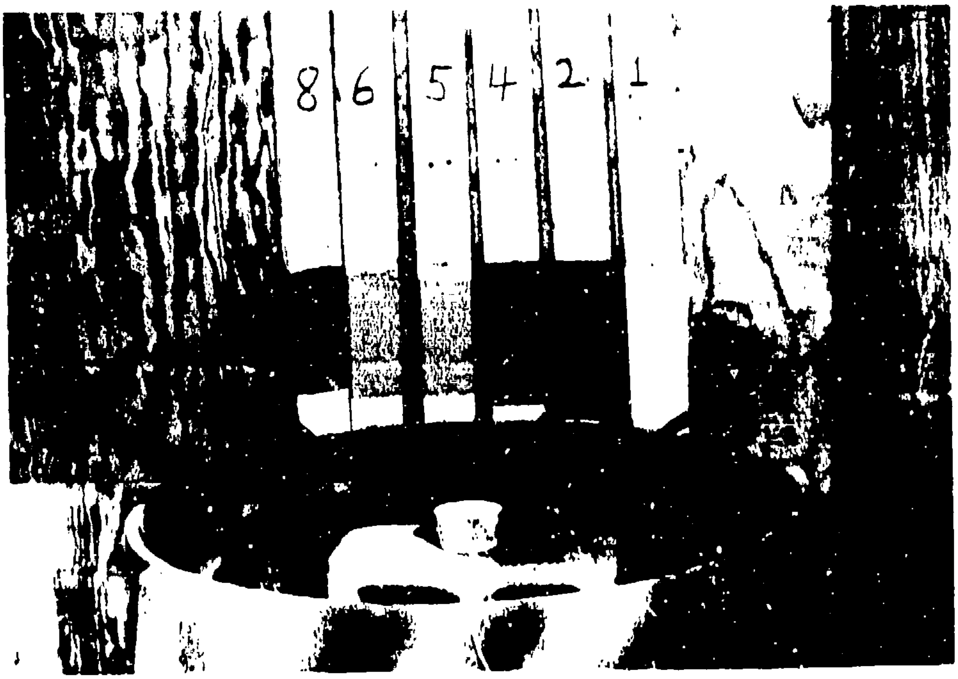


Figure 3. Test Set-Up For the Six
Candidate Coverall Materials

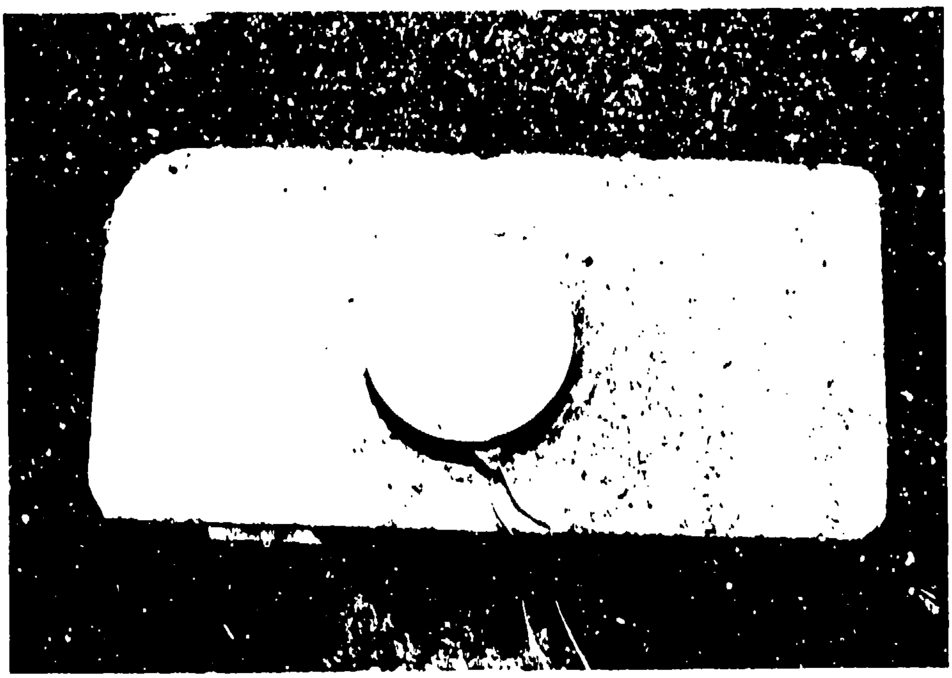


Figure 4. Pyrotechnic Source

Figure 5. Post Test Inspection of Single Layer Test

Figure 6. Post Test Inspection of Double Layer Test

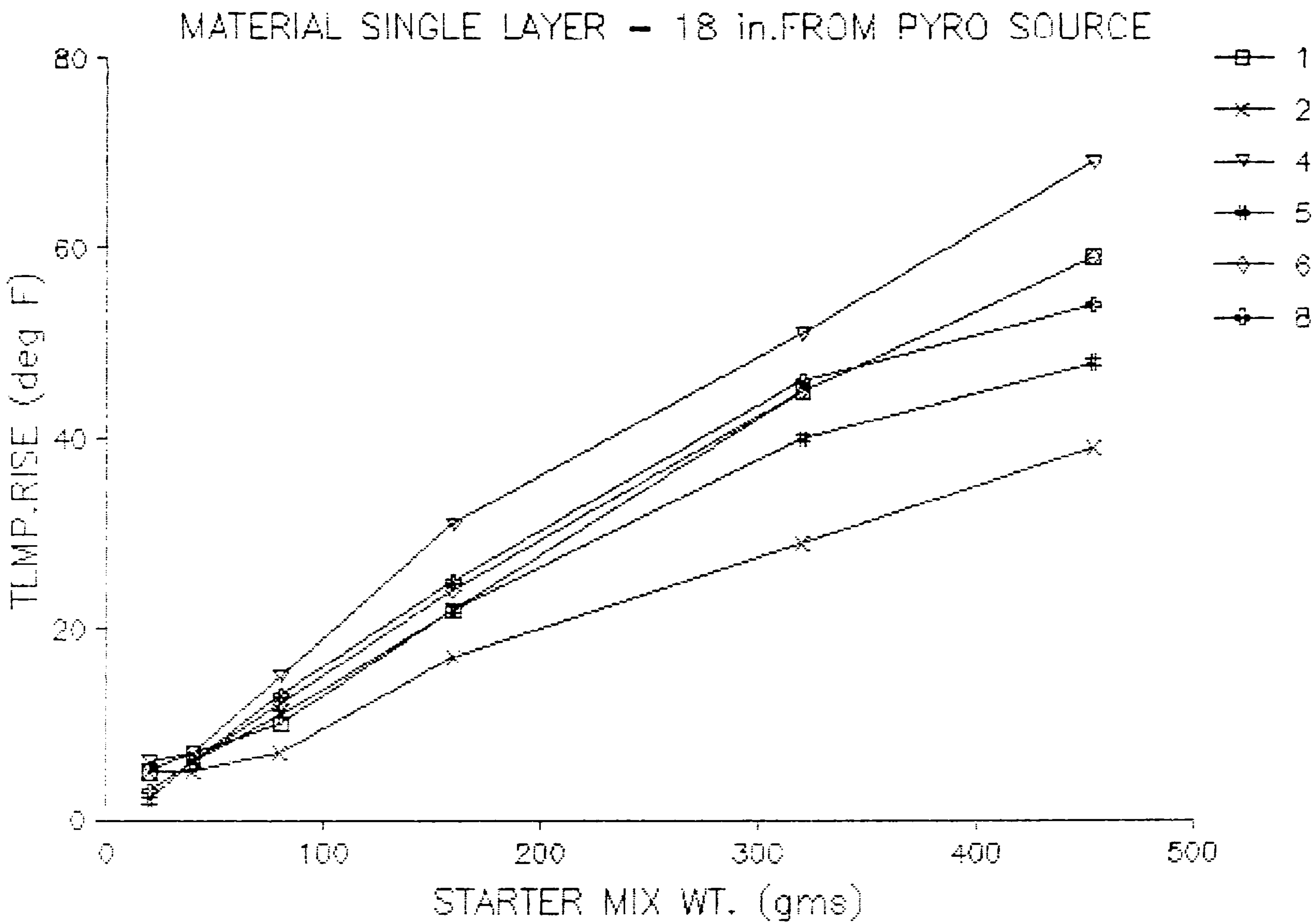


Figure 7. Skin Simulant Temperature Rise

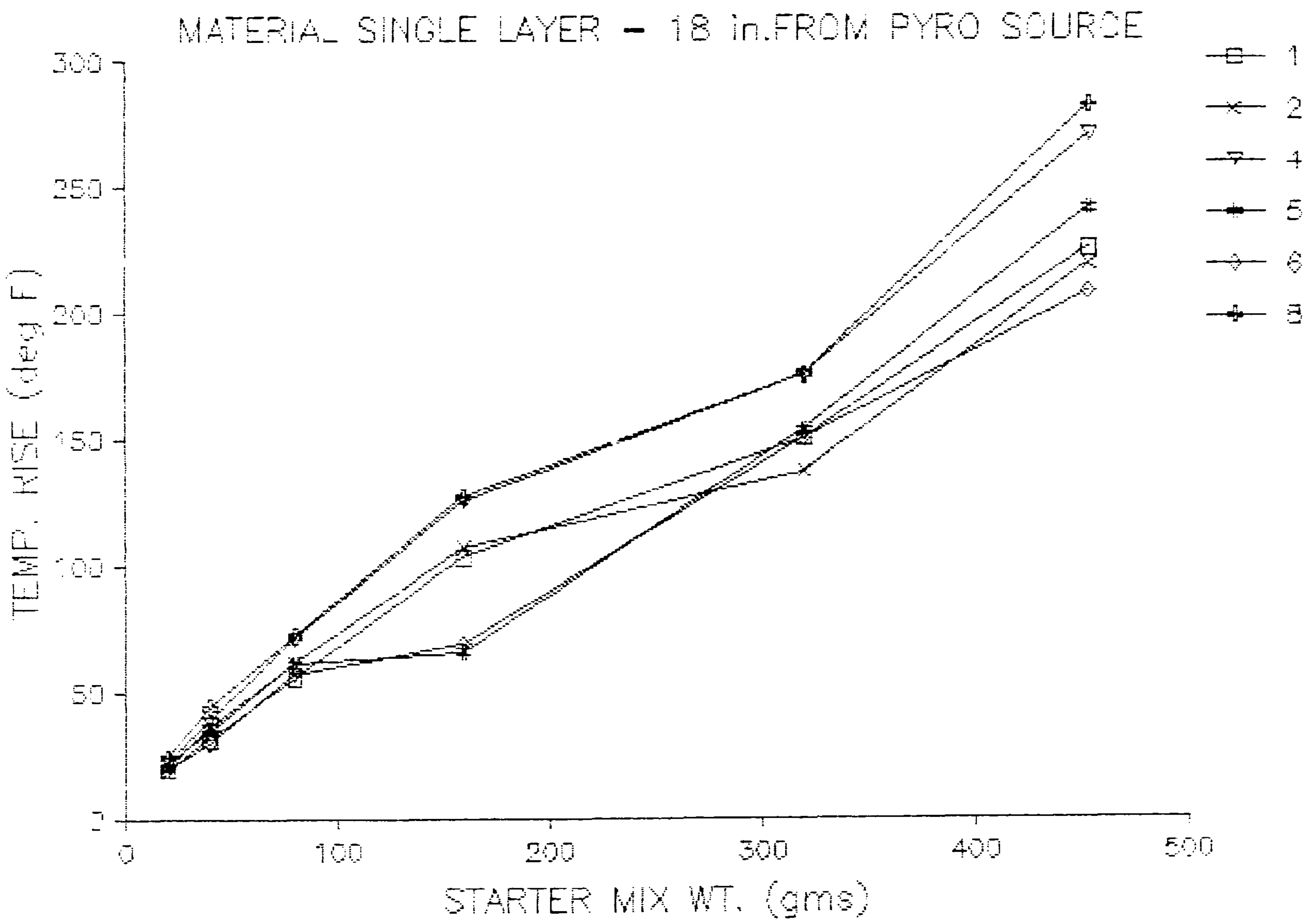


Figure 8. Exposed Thermocouple Temperature Rise

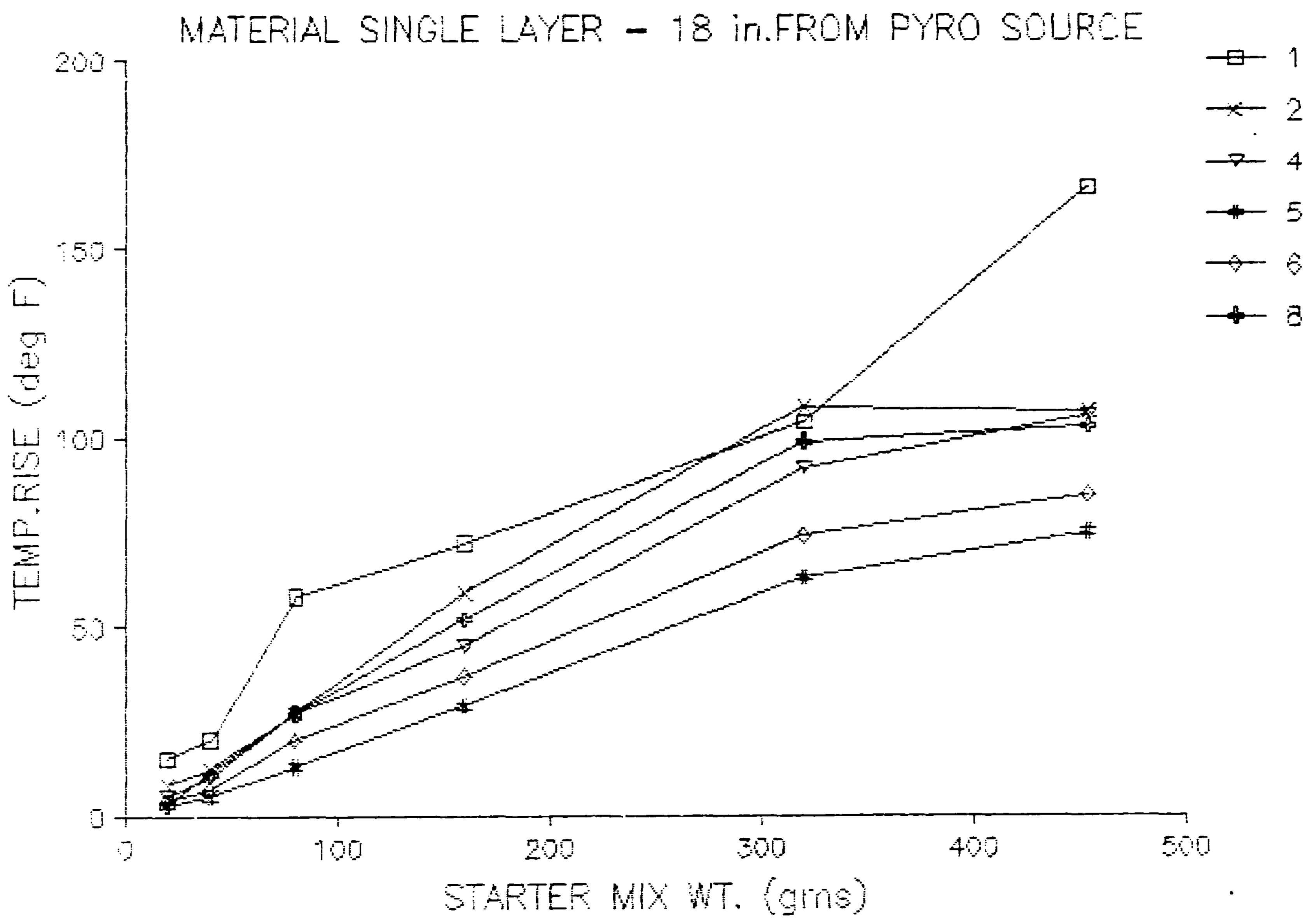


Figure 9. Covered Thermocouple Temperature Rise

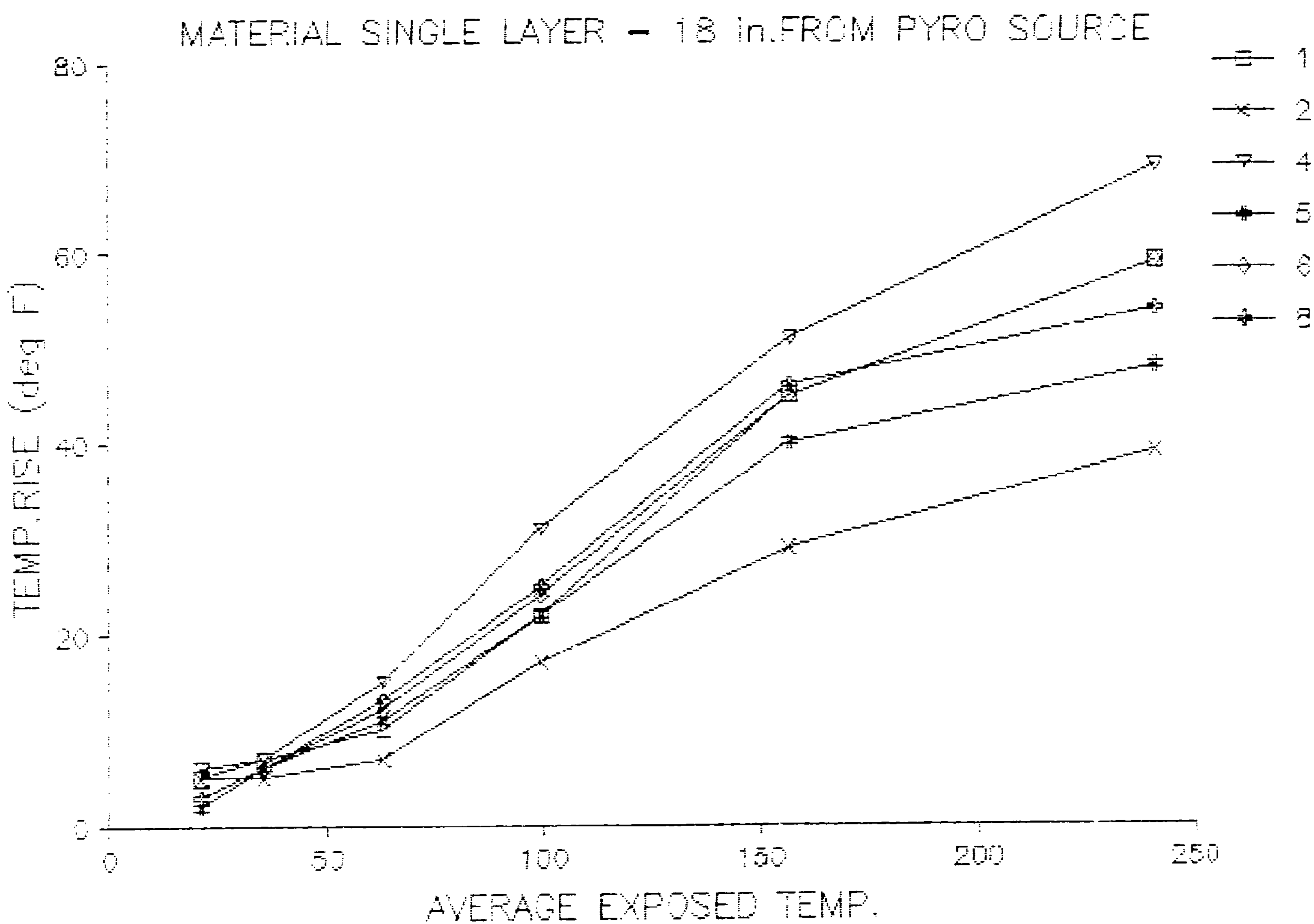


Figure 10. Skin Simulant Temperature Rise

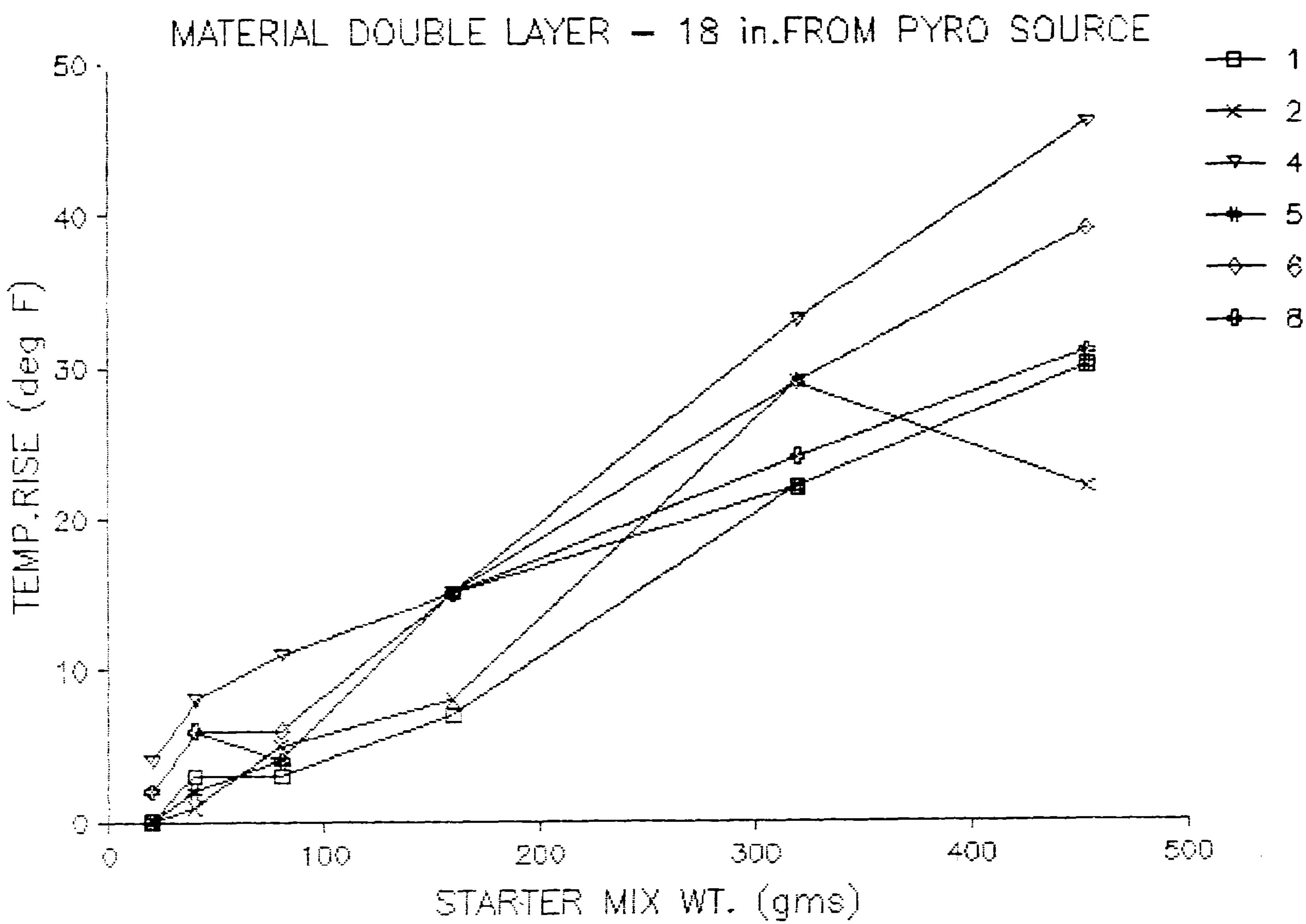


Figure 11. Skin Simulant Temperature Rise

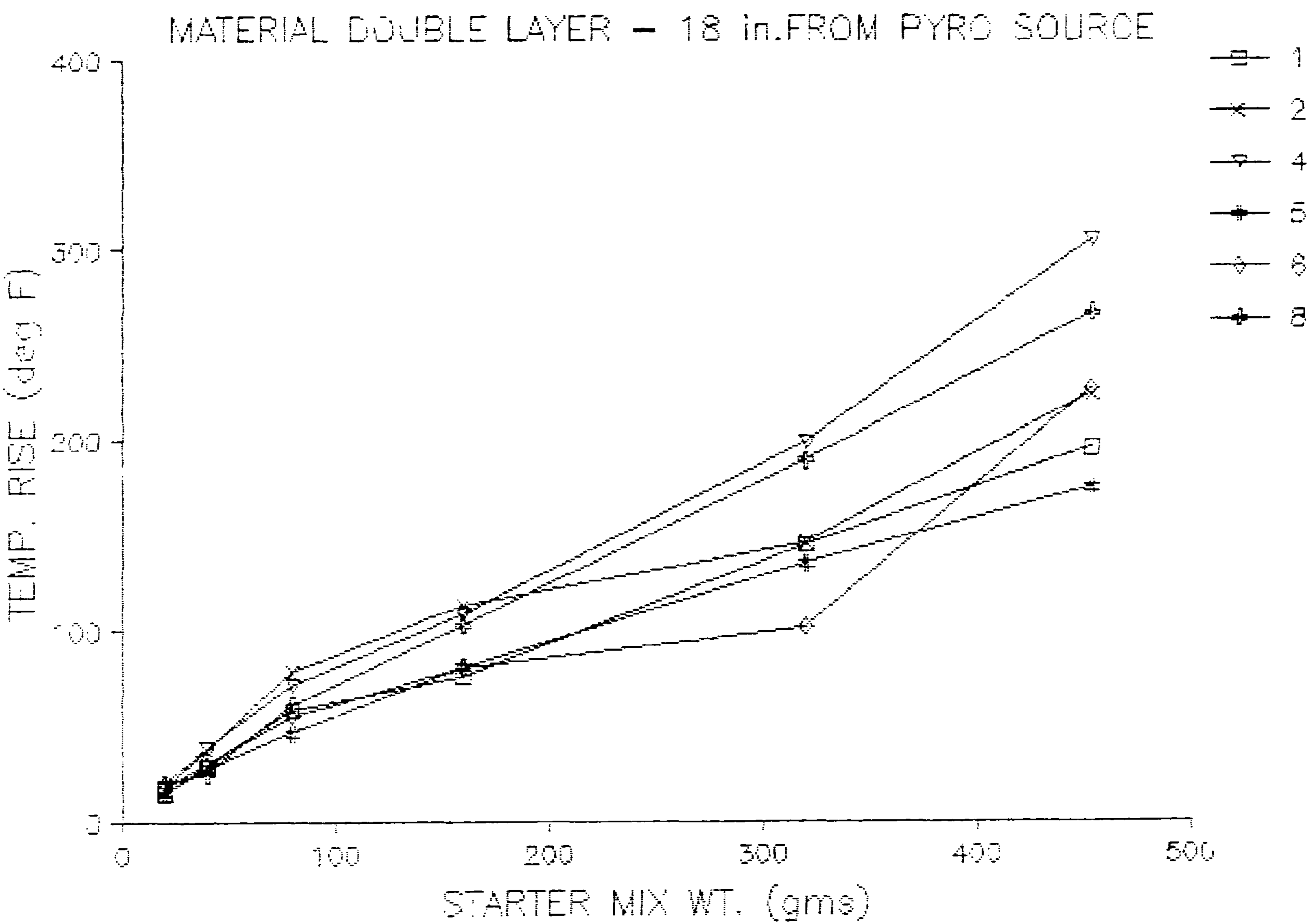


Figure 12. Exposed Thermocouple Temperature Rise

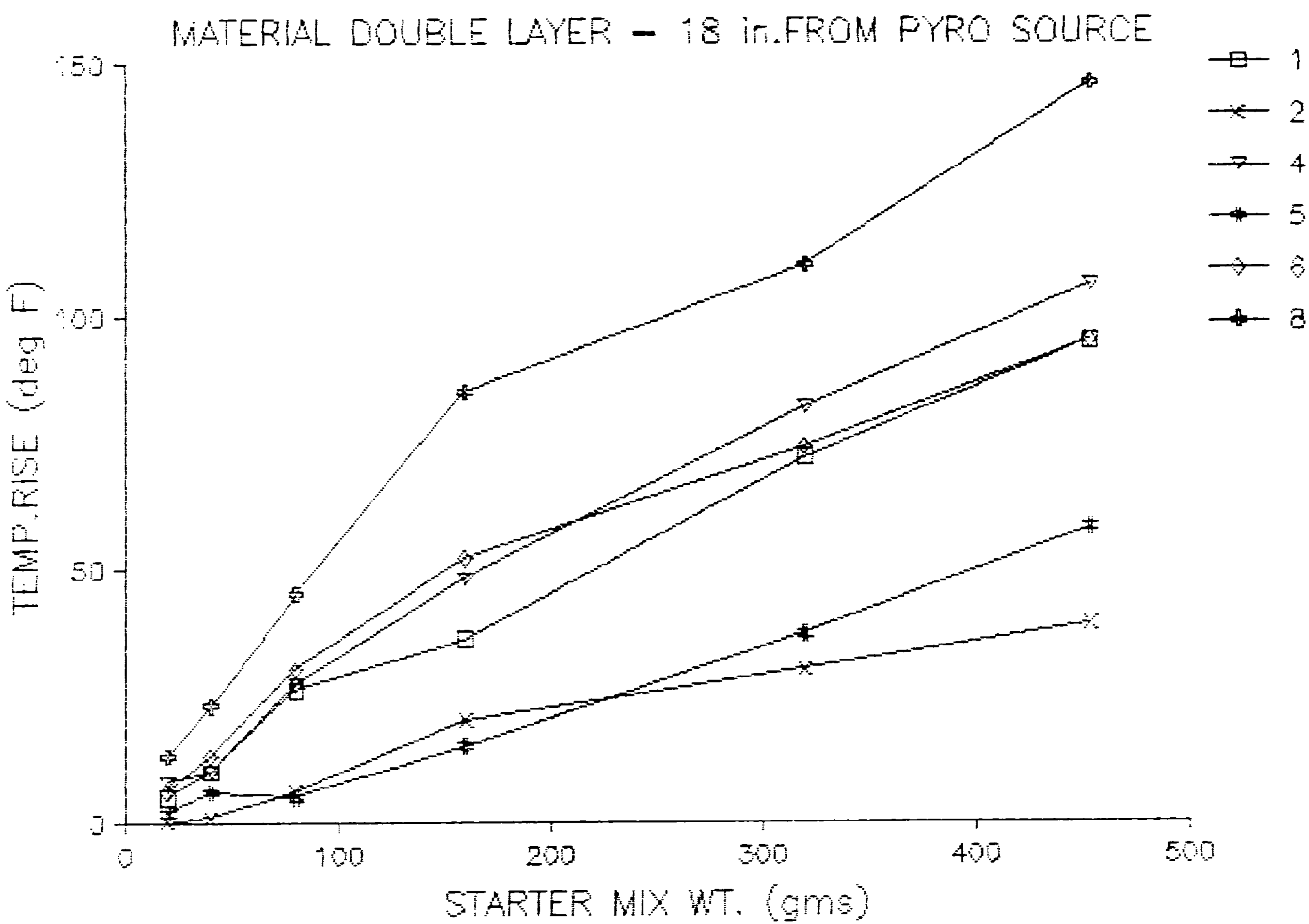


Figure 13. Covered Thermocouple Temperature Rise

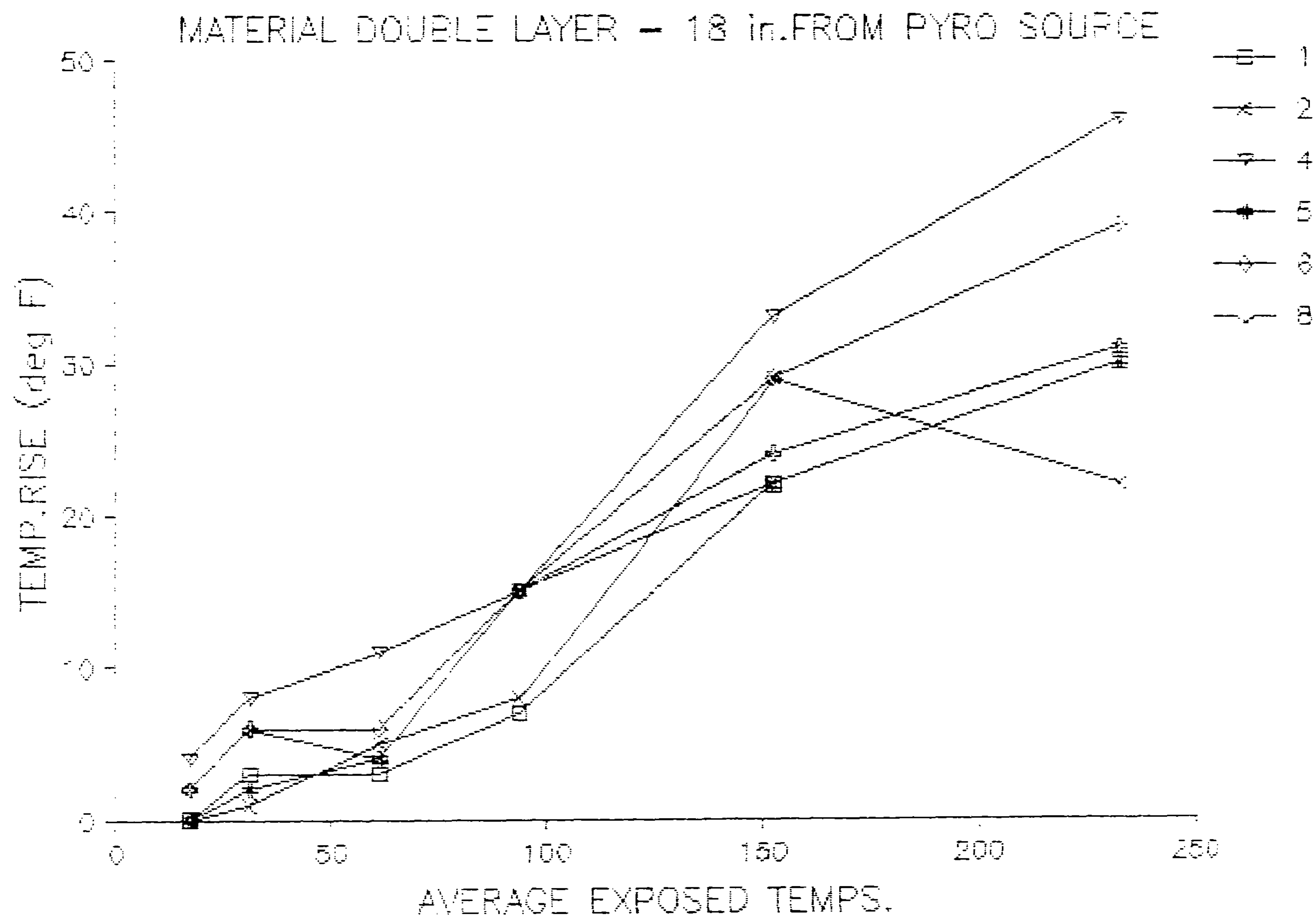


Figure 14. Skin Simulant Temperature Rise

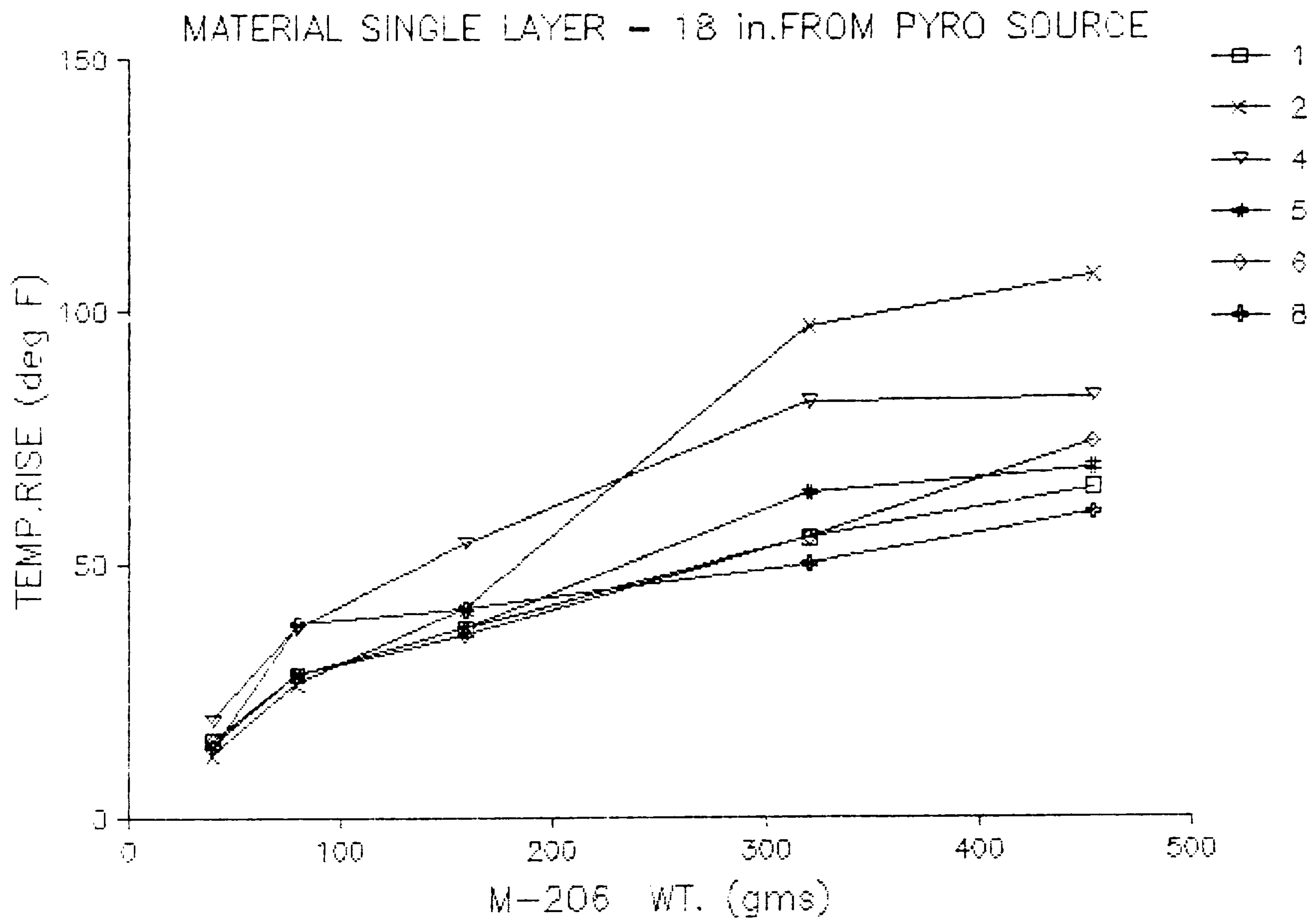


Figure 15. Skin Simulant Temperature Rise

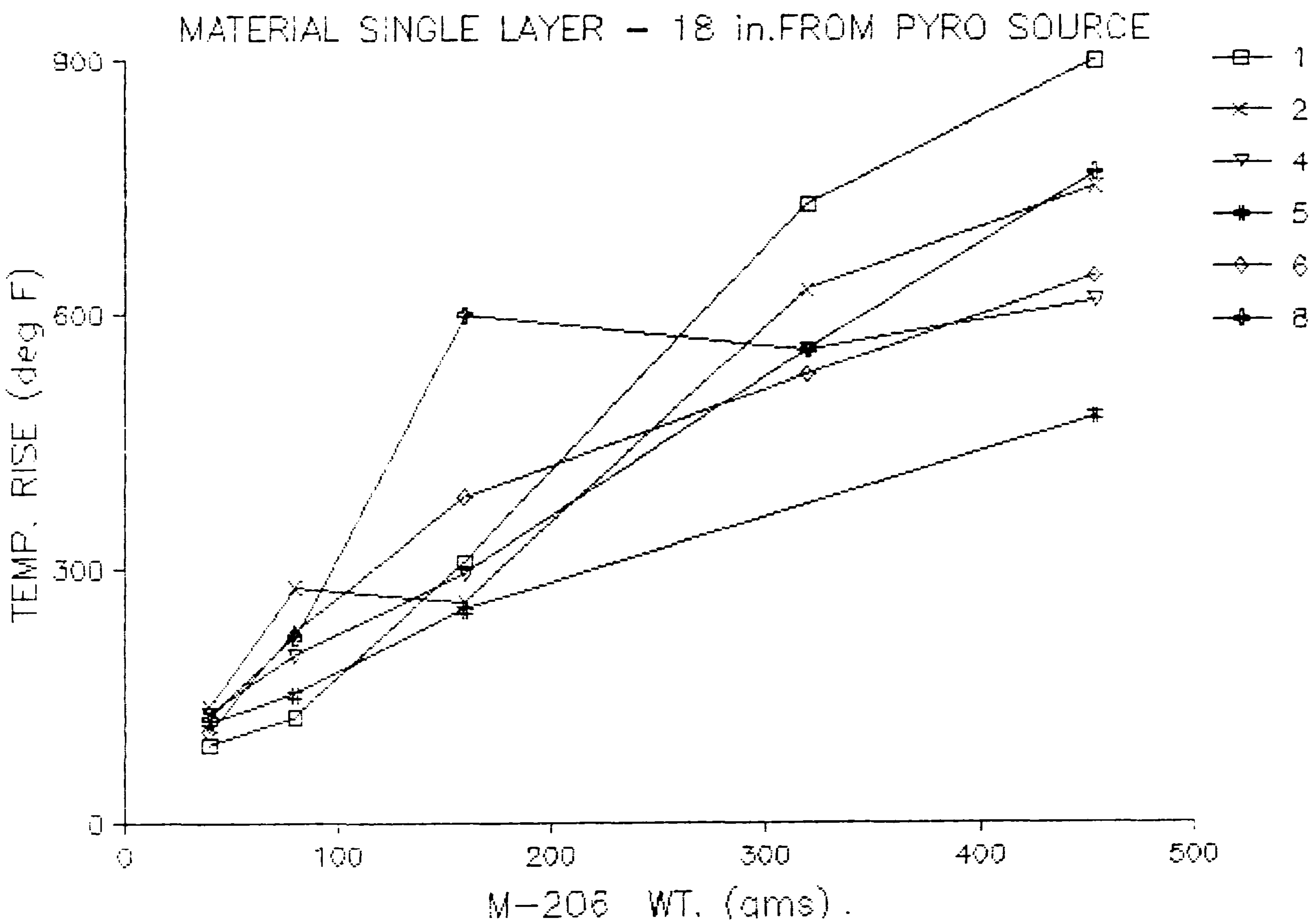


Figure 16. Exposed Thermocouple Temperature Rise

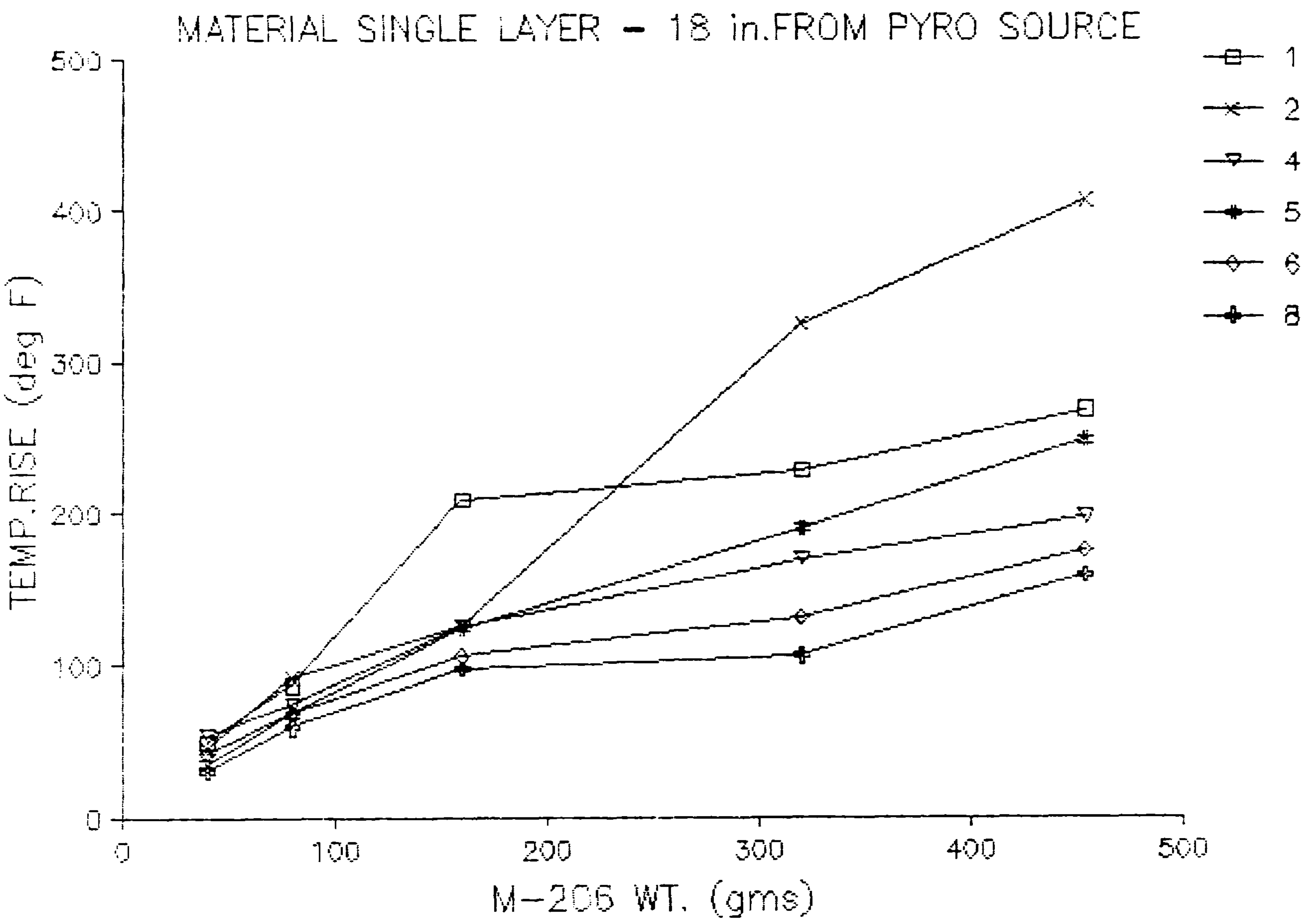


Figure 17. Covered Thermocouple Temperature Rise

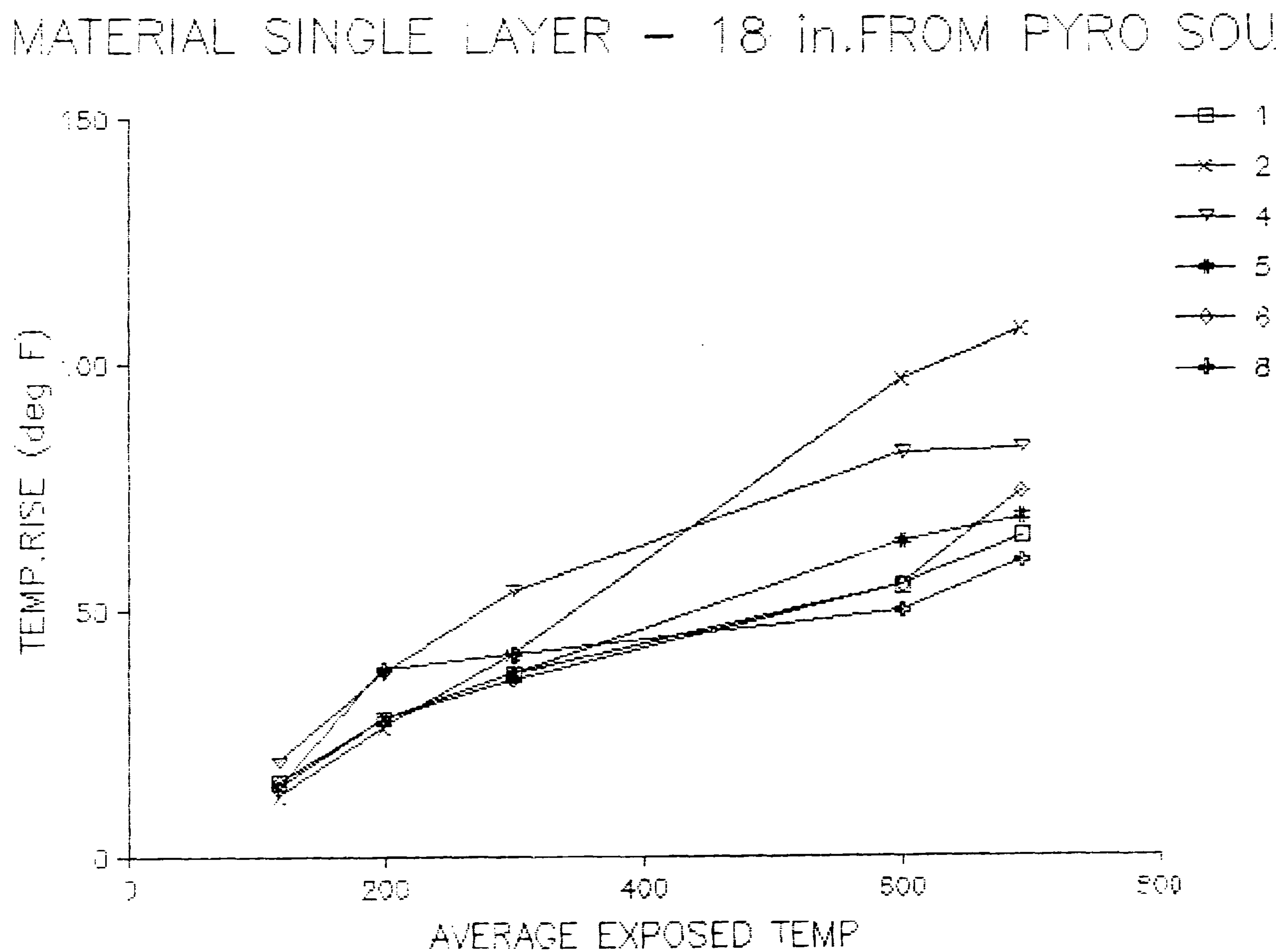


Figure 18. Skin Simulant Temperature Rise

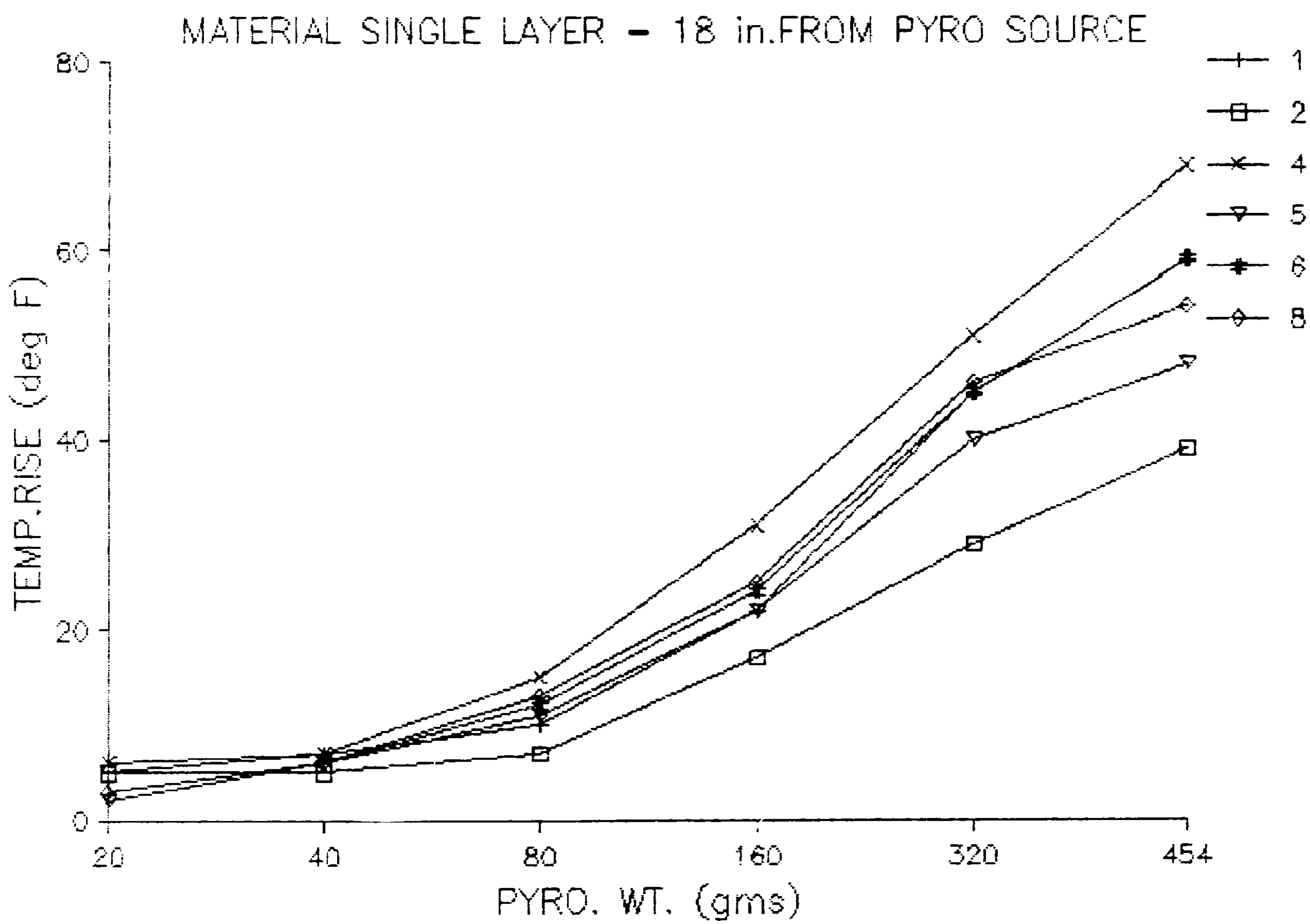


Figure 19. Skin Simulant Temperature Rise, Starter Mix Test

Figure 20. Single Layer Tests-320 grams

Figure 21. Single Layer Test-454 grams

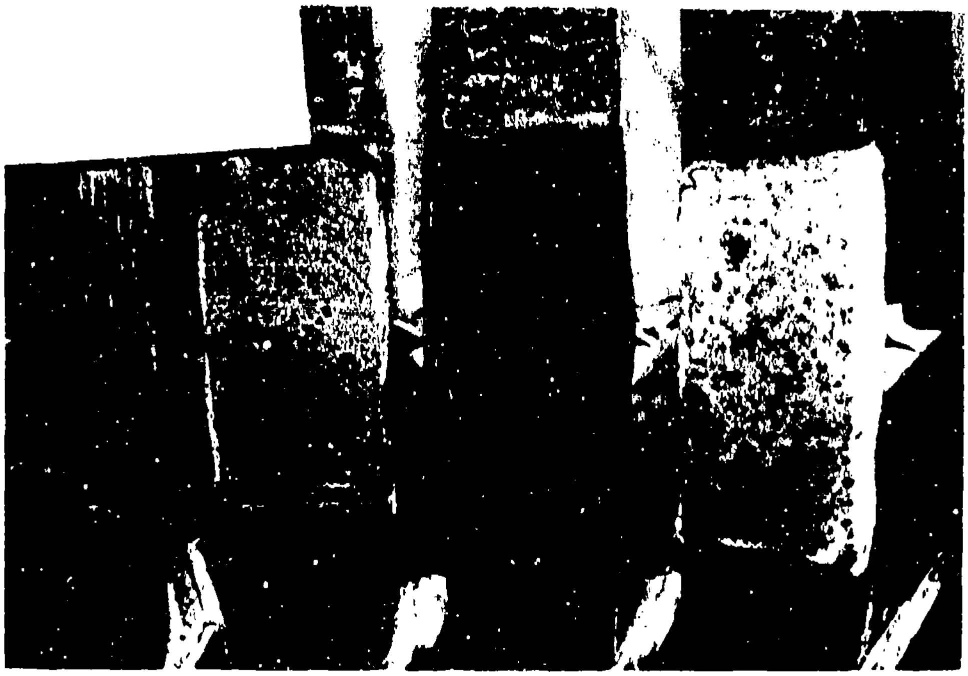


Figure 22. Single Layer Test-Close-Up View of Materials 1, 2, and 3-320 grams (NOTE: Material No. 2 has Split.)

Figure 23. Single Layer Test-Close-Up View of Materials 1, 2 and 3-454 grams (NOTE: Material No. 2 has Split.)

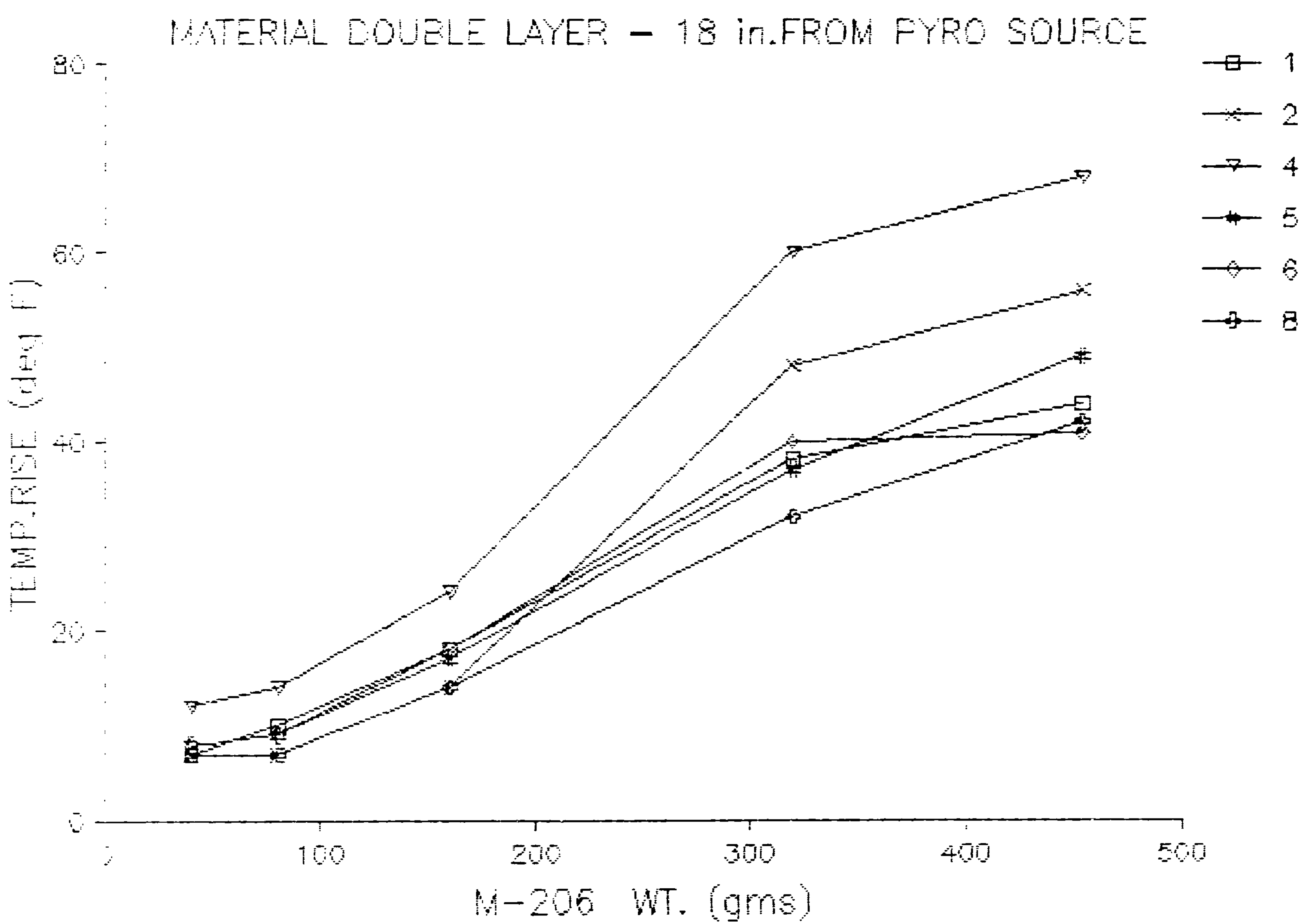


Figure 24. Skin Simulant Temperature Rise

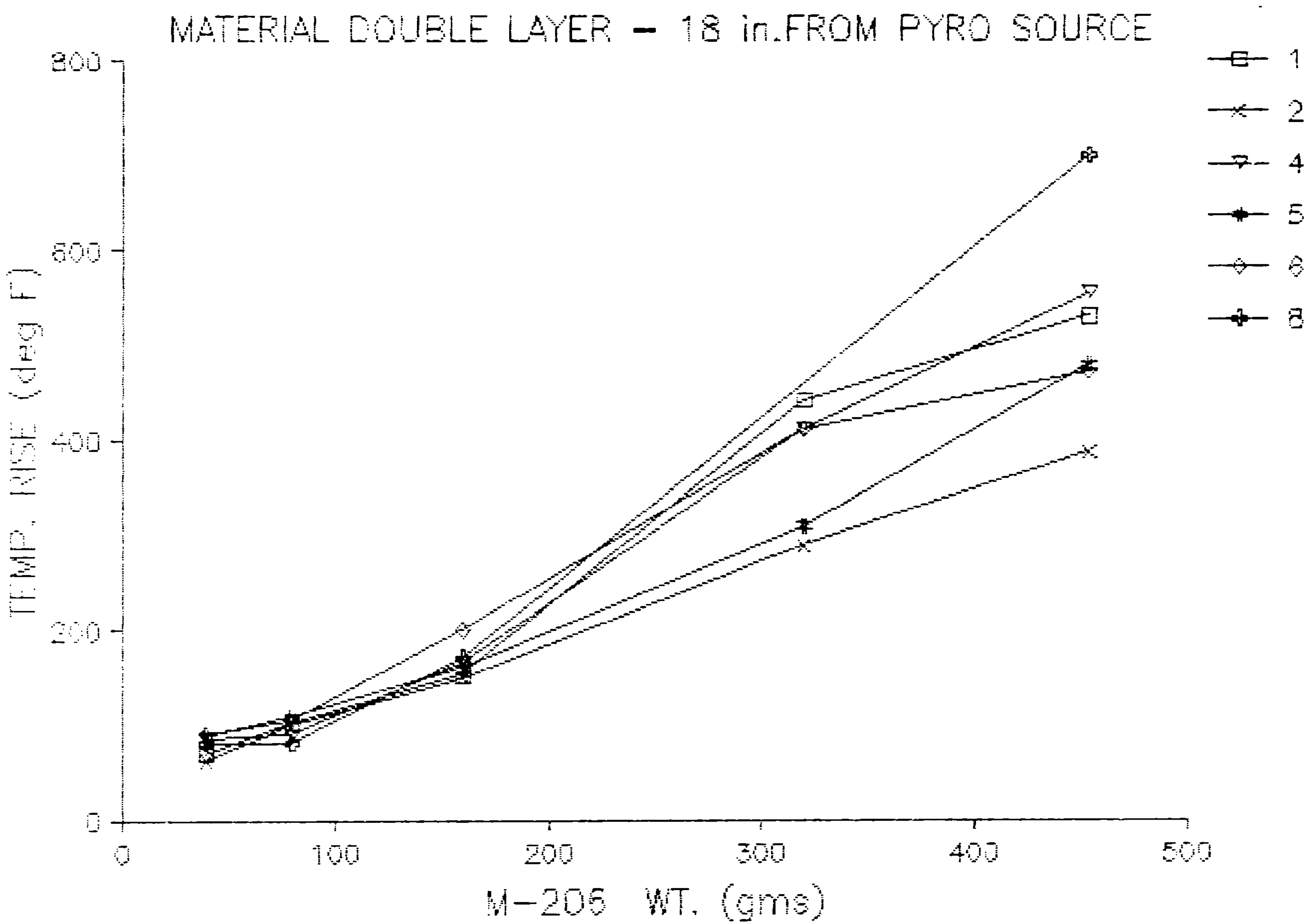


Figure 25. Exposed Thermocouple Temperature Rise

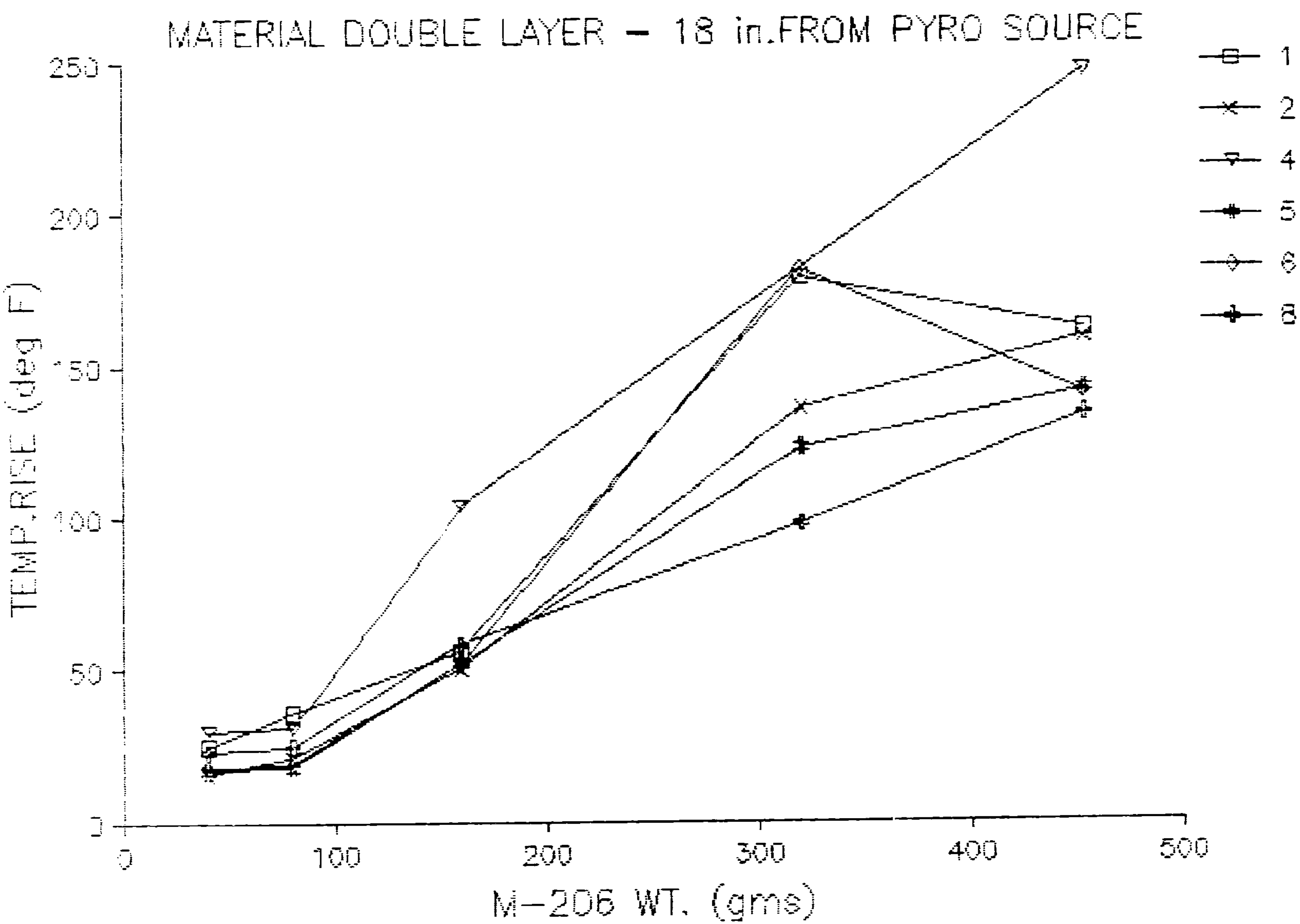
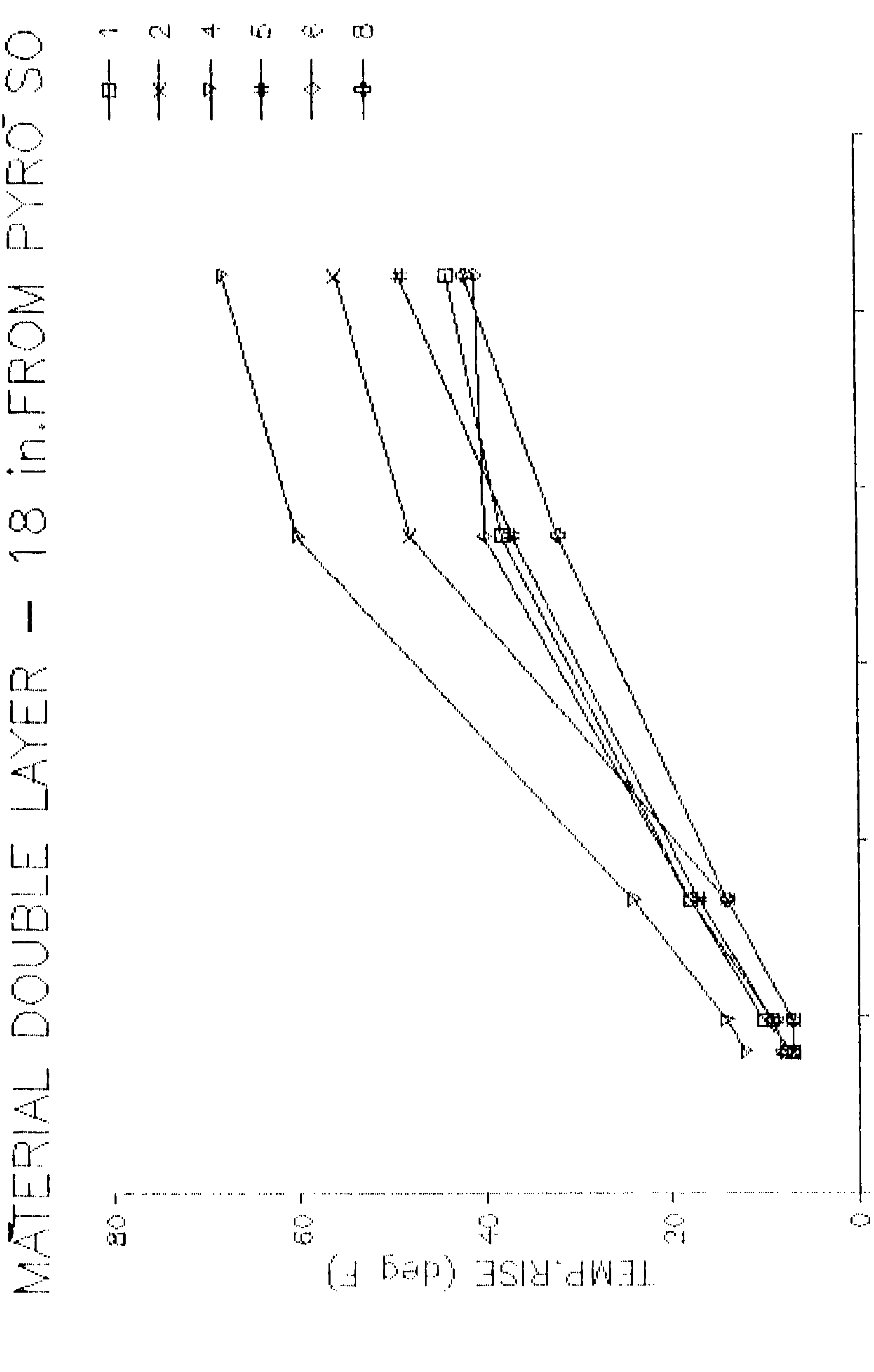


Figure 26. Covered Thermocouple Temperature Rise



MATERIAL DOUBLE LAYER — 18 in.FROM PYRO SO
TEMP.RISE (deg F)
0
20
40
60
80
AVERAGE EXPOSED TEMPS
0
100
200
300
400
500
600
1
2
4
5
6
8

Figure 28. Double Layer Test-320 grams

Figure 29. Double Layer Test-454 grams

APPENDIX

ELECTROSTATIC CHARGE RELAXATION CHARACTERISTICS
OF SIX FLAME RETARDANT FABRICS

This report summarizes the results of a series of experiments performed by Hazards Research Corporation, Rockaway, New Jersey, for Southwest Research Institute, of San Antonio, Texas, under Purchase Order No. 61958. Contact with Southwest Research Institute was maintained through Mr. Luis M. Vargas.

The purpose of this program was to determine the electrostatic charge relaxation characteristics of six flame retardant fabrics using standard test method ASTM D-2679-73. The "half-life" of induced electrical charges on the fabrics were to be determined before and after the samples were laundered.

A. MATERIALS

The client supplied the following six flame retardant fabrics for evaluation on this program:

No.	Sample	Description
1	Worklon, Nomex/Stainless Steel fiber (99/1)	Light yellow
2	Woven Cotton (100)	Dark blue, 8 oz./sq.
3	PBI/Nomex I (20/80)	Blue, 4.9 oz./sq.yd.
4	PBI/Kevlar/Durvil (35/35/30)	Tan, 7.5 oz./sq.yd.
5	PBI/Kevlar (40/60)	Gold, 4.5 oz./sq.yd.
6	PBI/PFR Rayon (20/80)	Blue/brown, 7.2 oz./sq.yd.

B. EQUIPMENT

Hazards Research supplied the following test equipment:

(1) Electrometer, Keithley Instruments Model 602

(2) Power Supply, Keithley Instruments Model 246

(3) Faraday Cup

(4) Recorder, Strip Chart, Hewlett Packard Model 7100B

(5) Hygrometer, Precision Model, Serdex

(6) Fabric sample holders

C. DESCRIPTION OF EXPERIMENTS

All experiments performed during this program were conducted in accordance with the requirements of ASTM Standard Test Method for Electrostatic Charge, D-2679-73 (Reapproved 1978). HRC fabricated the experimental apparatus shown in Figure 1. The apparatus consisted of a wooden frame that contained two parallel, six-inch square, stainless steel charging plates, spaced 0.75 inches apart. The plates were connected to the high-voltage power supply. The cloth sample, shown in Figure 2, was suspended by two wires that were grounded to the electrometer.

A typical experimental trial started by positioning the sample in between the charging plates for 30 seconds. Voltage levels of 700 to 3000 were used, depending on the fabric. At the end of 30 seconds, the sample was released. It was allowed to freefall into the Faraday Cup (Figure 3) a distance

sufficient to be below the entrance plane yet not touch any surface of the cup. Figure 4 shows the top and front views of the cup. The Faraday cup was connected to an electrometer and stripchart recorder. The electrometer was operated in the coulomb mode, and the recorder plotted the rate of charge decay, coulombs per second.

Relative humidity was not controlled by air-conditioning equipment; however, the experiments were purposely run in January and March when the relative humidity was normally low. Environmental temperatures were between 70°F and 75°F for all experiments, at relative humidity ranges of 30% to 41%. Ambient temperature and relative humidity were measured using the thermometer and precision hygrometer shown in Figure 5.

The experimental program was performed in two phases. Phase I measured the rate of charge decay of five swatches of each of the six fabrics in duplicate, for a total of 60 experiments. The samples were sent to the Navy Clothing and Textile Research Facility, in Natick, Massachusetts, where they were washed and dried 25 times according to their standard procedure. Phase II repeated the 60 experiments on the laundered samples in order to determine the effect of laundering on their relative rankings as charge dissipators.

D. DESCRIPTION OF EXPERIMENTAL METHODS

1. Electrical Charge Decay Measurements

A series of preliminary experiments with the charging

plates revealed that a cloth sample became fully charged after 30 seconds' exposure to the electrical field. The charge started to decay the instant the fabric left the electrical field. This rate of charge decay was measured using the Faraday cup shown in Figure 4. The apparatus consisted of a stainless steel cylinder, open at the top and connected to an electrometer. The entire cylinder was placed within a slightly larger stainless steel cylinder that was separated from the inside cylinder by Teflon rods. The outer container was grounded in order to provide a Faraday cage effect (shield out stray fields).

A positively-charged cloth sample entering the air space of the inside vessel attracts a negative charge to the inside wall of the vessel. This leaves an excess of positive charges on the sensing device in the electrometer. As the charges on the cloth sample dissipate to the air and through the ground wire, the electrometer registers this loss. The rate of charge decay, coulombs per second, is plotted by the stripchart recorder that is connected to the output terminal of the electrometer.

2. Data Reduction Technique

The relaxation time is the total time required for a charged cloth sample to dissipate by leakage. The

approach used on this program was to use the "half-life" as the basis for comparison of results. "Half-life" is the time for the initial charge on the fabric to fall 50%. Figure 6 is a typical charge-vs.-time trace, with the values of the initial charge, 50% charge, and corresponding "half-life" noted. For flat plate condensers, the "half-life" is given by the following equation:

$$t_{\frac{1}{2}} = 0.693\, t_r \quad (\textit{Ref. 1})$$

Where: t_r = relaxation time, seconds

E. EXPERIMENTAL RESULTS

1. Unlaundered Cloth Samples

A total of 60 charge relaxation experiments were performed on six flame retardant fabrics. Table 1 presents the results of this Phase I effort.

2. Laundered Cloth Samples

Phase II results are presented in Table 2. It is seen that a total of 60 charge relaxation experiments were performed on the laundered cloth samples.

Table 3 presents a comparison of the average relative "half-life" values for laundered and unlaundered samples. A summary of experimental results is presented in Table 4.

Ref. 1. F.G. Eichel, "Electrostatics", Chemical Engineering, March 13, 1967, pp. 153-167.

F. DISCUSSION OF RESULTS

Data analysis was simplified by calculating a relative "half-life" for each series of 12 letter-grouped trials. Each "half-life" value was determined by dividing the individual "half-life" values in the series by the lowest "half-life" of the series. For example, in Table 1, the first 1A trial yielded a "half-life" of 1.70 seconds. The first 4A trial had the shortest "half-life", 0.15 seconds, of the series. Therefore, the relative "half-life" of the first 1A trial is 1.7/0.15 = 11.33. The average relative "half-life" values of each A, B, C, D and E group were then calculated and tabulated in Table 3. For example, sample 2A had "half-life" values of 25.67 seconds and 26.67 seconds, respectively. Their average value in Table 3 is 26.17 seconds.

Table 3 presents a comparison of the average relative "half-life" values for the unlaundered and laundered fabrics. The fabrics are rated in order of increasing relaxation time. It is seen that sample number 4 (PBI/Kevlar/Durvil) is the fastest electrostatic charge dissipator both before and after laundering.

Table 4 presents a summary of the experimental results. It is seen that laundering did not affect the charge relaxation ratings of the woven cotton, PBI/Kevlar/Durvil and PBI/PFR Rayon samples. Laundering significantly improved the PBI/Nomex I

rating, changing it from sixth place to second place. Nomex/SST went from fourth to sixth place as a result of laundering, while PBI/Kevlar dropped from second to fourth place.

Laundering appears to increase the rate of charge dissipation. The magnitude of the effect differs between fabrics. It is noted that prior to laundering, there were greater differences between the average relative "half-life" values. After laundering, these differences were significantly reduced. A possible explanation is that some residual surface active agent may have been absorbed on the surface of the fabric. This caused the fabrics to become more conductive.

G. CONCLUSIONS

As a result of 120 electrostatic charge relaxation experiments performed on six flame retardant fabrics, it is possible to conclude the following:

1. The PBI/Kevlar/Durvil samples dissipate the induced static charges faster than any of the five other fabrics in both the unlaundered and laundered conditions. "Half-life" charge relaxation times were $\leq$0.80 seconds. Materials that relax charge in 1.0 second or less are not considered to be viable electrostatic discharge ignition hazards.

2. The PBI/Kevlar samples rank second in charge dissipation rate in the unlaundered condition. Laundering lowers the ranking to fourth place.

3. The PBI/PFR Rayon samples rank third in charge dissipation rate in both the unlaundered and laundered conditions.

4. The Nomex/SST samples rank fourth in charge dissipation rate in the unlaundered condition. Laundering lowers the ranking to sixth place.

5. The woven cotton samples rank fifth in charge dissipation rate in both the unlaundered and laundered conditions.

6. The PBI/Nomex I samples rank sixth in charge dissipation rate in the unlaundered condition. Laundering raises the ranking to second place.

7. Laundering increases the rate of charge relaxation of all fabrics. The magnitude of the increase varies significantly between fabrics. The greatest improvement occurs in the PBI/Nomex I fabric.

8. Since laundering appears to increase the electrical conductivity of all six fabrics, the selection of a fabric for a specific application should be based on the unlaundered test results.

Table 1. Results of charge relaxation experiments performed on six unlaundered, flame retardant fabrics

Sample no.	Ambient conditions			Charge (coulombs) 10^{-9}		"Half-life"	Rel. "half-life"
	Temp. (^{o}F)	R.H. (%)	Corr. R.H. (%)	Qo	Qo/2	$t_{1/2}$ (sec.)	
1A	74	37	42	3.08	1.54	1.70	11.3
1A	74	37	42	1.35	0.68	0.30	2.0
2A	74	37	42	10.00	5.00	3.85	25.7
2A	74	37	42	10.00	5.00	4.00	26.7
3A	74	37	42	10.00	5.00	2.85	19.0
3A	74	37	42	10.00	5.00	2.95	19.7
4A	73	37	41	5.69	2.85	0.15	1.0
4A	73	37	41	6.05	3.03	0.20	1.3
5A	73	38	41	6.62	3.31	0.80	5.3
5A	73	38	41	9.71	4.86	0.85	5.7
6A	73	38	41	8.11	4.06	1.00	6.7
6A	73	38	41	6.88	3.44	1.20	8.0

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70^{o}F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{1/2}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 1. Results of charge relaxation experiments performed on six unlaundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions			Charge		"Half-life"	Rel. "half-life"
	Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Qo (coulombs)10^{-9}	Qo/2	$t_{½}$ (sec.)	
1B	75	37	43	1.47	0.74	1.00	10.0
1B	75	37	43	2.21	1.10	1.20	12.0
2B	75	37	43	6.43	3.20	5.00	50.0
2B	75	37	43	5.71	2.86	5.20	52.0
3B	75	37	43	8.85	4.43	3.10	31.0
3B	75	37	43	9.03	4.52	3.15	31.5
4B	75	37	43	6.56	3.28	0.10	1.0
4B	75	37	43	6.00	3.10	0.10	1.0
5B	75	37	43	7.32	3.66	0.90	9.0
5B	75	37	43	7.86	3.93	0.95	9.5
6B	75	37	43	3.62	1.81	0.50	5.0
6B	75	37	43	3.21	1.61	0.35	3.5

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{½}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 1. Results of charge relaxation experiments performed on six unlaundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions			Charge (coulombs) 10^{-9}		"Half-life" $t_{1/2}$ (sec.)	Rel. "half-life"
	Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Qo	Qo/2		
1C	75	35	41	3.96	1.98	18.60	46.5
1C	75	35	41	4.28	2.14	19.50	48.7
2C	75	34	41	8.70	4.35	11.05	27.6
2C	75	34	41	9.53	4.77	12.80	32.0
3C	75	34	41	7.48	3.74	3.65	9.1
3C	75	34	41	8.36	4.18	3.65	9.1
4C	75	34	41	8.43	4.22	0.45	1.1
4C	75	34	41	8.22	4.11	0.40	1.0
5C	75	34	41	9.68	4.84	1.20	3.0
5C	75	34	41	9.90	4.95	1.05	2.6
6C	75	34	41	9.39	4.70	1.05	2.6
6C	75	34	41	9.39	4.70	1 00	2.5

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{1/2}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 1. Results of charge relaxation experiments performed on six unlaundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions			Charge		"Half-life"	Rel. "half-life"
	Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Qo (coulombs)10^{-9}	Qo/2	$t_{1/2}$ (sec.)	
1D	73	31	35	2.51	1.26	9.25	16.8
1D	73	31	35	2.23	1.12	4.00	7.3
2D	73	31	35	8.67	4.34	12.00	21.8
2D	73	31	35	8.88	4.44	14.30	26.0
3D	73	31	35	8.18	4.09	6.40	11.6
3D	73	31	35	10.00	5.00	7.10	12.9
4D	73	31	35	6.21	3.11	0.80	1.4
4D	73	31	35	7.11	3.56	0.55	1.0
5D	73	31	35	5.62	2.81	1.50	2.7
5D	73	31	35	5.56	2.78	1.85	3.4
6D	73	31	35	10.00	5.00	2.20	4.0
6D	73	31	35	10.00	5.00	2.10	3.8

Legend:

R.H.	=	Relative Humidity
Corr. R.H.	=	Corrected Relative Humidity to 70°F
Qo	=	Total charge on sample fabric
Qo/2	=	50% of Qo
$t_{1/2}$	=	Elapsed time between Qo and Qo/2 = "half-life"

Table 1. Results of charge relaxation experiments performed on six unlaundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Charge Qo (coulombs)10^{-9}	Qo/2	"Half-life" $t_{1/2}$ (sec.)	Rel. "half-life"
1E	73	29	32	0.92	0.46	2.75	5.0
1E	73	29	32	1.17	0.59	3.55	6.4
2E	73	29	32	8.96	4.48	12.50	22.7
2E	73	29	32	9.49	4.75	13.25	24.1
3E	73	29	32	9.20	4.60	7.80	14.8
3E	73	29	32	8.78	4.39	7.80	14.2
4E	73	29	32	6.72	3.36	0.55	1.0
4E	73	29	32	8.52	4.26	0.60	1.1
5E	74	30	34	10.00	5.00	2.40	4.4
5E	74	30	34	10.00	5.00	2.50	4.5
6E	74	30	34	7.80	3.90	2.90	5.3
6E	74	30	34	7.38	3.69	2.40	4.4

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{1/2}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 2. Results of charge relaxation experiments performed on six laundered, flame retardant fabrics

Sample no.	Ambient conditions			Charge		"Half-life"	Rel. "half-life"
	Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Qo (coulombs)10^{-9}	Qo/2 (coulombs)10^{-9}	$t_{1/2}$ (sec.)	
1A	73	38	41	1.80	0.90	2.70	18.0
1A	73	38	41	1.50	0.75	0.15	1.0
2A	71	40	41	7.08	3.54	4.80	32.0
2A	71	40	41	7.90	3.95	5.45	36.3
3A	71	40	41	6.40	3.20	0.25	1.7
3A	71	40	41	6.60	3.30	0.40	2.7
4A	70	40	40	4.65	2.33	0.20	1.3
4A	70	40	40	4.37	2.19	0.30	2.0
5A	70	40	40	6.10	3.05	0.80	5.3
5A	70	40	40	5.66	2.83	0.90	6.0
6A	70	40	40	3.41	1.71	1.70	11.3
6A	70	40	40	4.00	2.00	2.00	13.3

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{1/2}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 2. Results of charge relaxation experiments performed on six laundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions			Charge		"Half-life"	Rel. "half-life"
	Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Qo (coulombs) 10^{-9}	Qo/2 (coulombs) 10^{-9}	$t_{1/2}$ (sec.)	
1B	70	40	40	3.28	1.64	18.40	122.7
1B	70	40	40	3.00	1.50	23.45	156.3
2B	70	40	40	4.45	2.23	4.60	30.7
2B	70	40	40	3.98	1.99	4.80	32.0
3B	70	40	40	4.02	2.01	0.20	1.3
3B	70	40	40	4.61	2.30	0.20	1.3
4B	70	40	40	1.87	0.94	0.15	1.0
4B	70	40	40	1.79	0.90	0.15	1.0
5B	70	40	40	3.50	1.75	0.65	4.3
5B	70	40	40	3.64	1.82	0.70	4.7
6B	70	40	40	2.21	1.10	0.90	6.0
6B	70	40	40	3.65	1.83	0.80	5.3

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{1/2}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 2. Results of charge relaxation experiments performed on six laundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Charge Qo (coulombs)10^{-9}	Qo/2	"Half-life" $t_{1/2}$ (sec.)	Rel. "half-life"
1C	73	41	45	1.40	0.70	0.30	2.0
1C	73	41	45	1.96	0.98	0.55	3.7
2C	73	41	45	0.90	0.45	0.25	1.7
2C	73	41	45	1.28	0.64	0.50	3.3
3C	73	41	45	6.37	3.19	0.15	1.0
3C	73	41	45	6.29	3.15	0.20	1.3
4C	73	41	45	1.80	0.90	0.30	2.0
4C	73	41	45	2.52	1.26	0.25	1.7
5C	73	41	45	2.83	1.42	0.70	4.7
5C	73	41	45	3.73	1.87	0.60	4.0
6C	73	41	45	4.08	2.04	0.40	2.7
6C	73	41	45	3.88	1.94	0.30	2.0

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{1/2}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 2. Results of charge relaxation experiments performed on six laundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Charge Qo (coulombs) 10^{-9}	Qo/2	"Half-life" $t_{½}$ (sec.)	Rel. "half-life"
1D	70	41	41	1.75	0.87	0.55	2.8
1D	70	41	41	1.90	0.95	0.55	2.8
2D	70	41	41	2.98	1.49	2.10	10.5
2D	70	41	41	4.59	2.30	4.00	20.0
3D	70	41	41	4.88	2.44	0.30	1.5
3D	70	41	41	5.15	2.58	0.35	1.8
4D	70	41	41	1.05	0.53	0.20	1.0
4D	70	41	41	1.63	0.82	0.25	1.2
5D	70	41	41	4.09	2.05	0.75	3.7
5D	70	41	41	5.50	2.75	0.65	3.2
6D	70	41	41	4.44	2.22	0.40	2.0
6D	70	41	41	5.48	2.74	0.40	2.0

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{½}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 2. Results of charge relaxation experiments performed on six laundered, flame retardant fabrics (cont.)

Sample no.	Ambient conditions			Charge		"Half-life"	Rel. "half-life"
	Temp. (°F)	R.H. (%)	Corr. R.H. (%)	Qo (coulombs) 10^{-9}	Qo/2	$t_{½}$ (sec.)	
1E	70	40	40	3.10	1.60	5.60	18.7
1E	70	40	40	2.32	1.16	2.45	8.2
2E	70	40	40	2.81	1.40	2.60	8.7
2E	70	40	40	3.52	1.76	4.50	15.0
3E	70	40	40	6.30	3.15	0.35	1.2
3E	70	40	40	6.77	3.39	0.35	1.2
4E	70	40	40	1.36	0.68	0.30	1.0
4E	70	40	40	1.52	0.76	0.30	1.0
5E	70	40	40	3.72	1.86	0.70	2.3
5E	70	40	40	4.61	2.30	0.70	2.3
6E	70	40	40	2.93	1.47	0.45	1.5
6E	70	40	40	3.48	1.74	0.40	1.3

Legend:

R.H. = Relative Humidity
Corr. R.H. = Corrected Relative Humidity to 70°F
Qo = Total charge on sample fabric
Qo/2 = 50% of Qo
$t_{½}$ = Elapsed time between Qo and Qo/2 = "half-life"

Table 3. Comparison of average relative "half-life" values

Unlaundered fabrics

Sample no.	Average relative "half-lives", seconds A	B	C	D	E	Charge Relaxation Rating
1	6.7	11.0	47.6	12.0	5.7	4
2	26.2	51.0	29.8	23.9	23.4	5
3	19.3	31.2	9.1	12.2	14.5	6
4	1.1	1.0	1.0	1.2	1.0	1
5	5.5	9.2	2.8	3.0	4.4	2
6	7.3	4.2	2.5	3.9	4.8	3

Laundered fabrics

Sample no.	A	B	C	D	E	Charge Relaxation Rating
1	9.5	139.5	2.8	2.8	13.4	6
2	34.1	31.3	2.5	15.2	11.8	5
3	2.2	1.3	1.1	1.6	1.2	2
4	1.6	1.0	1.8	1.1	1.0	1
5	5.6	4.5	4.3	3.4	2.3	4
6	12.3	5.6	2.3	2.0	1.4	3

Table 4. Summary of experimental results

Sample	Charge relaxation rating Unlaundered	Laundered
1) Nomex/SST (99/1)	4	6
2) Woven Cotton (100)	5	5
3) PBI/Nomex I (20/80)	6	2
4) PBI/Kevlar/Durvil	1	1
5) PBI/Kevlar (40/60)	2	4
6) PBI/PFR Rayon (20/80)	3	3

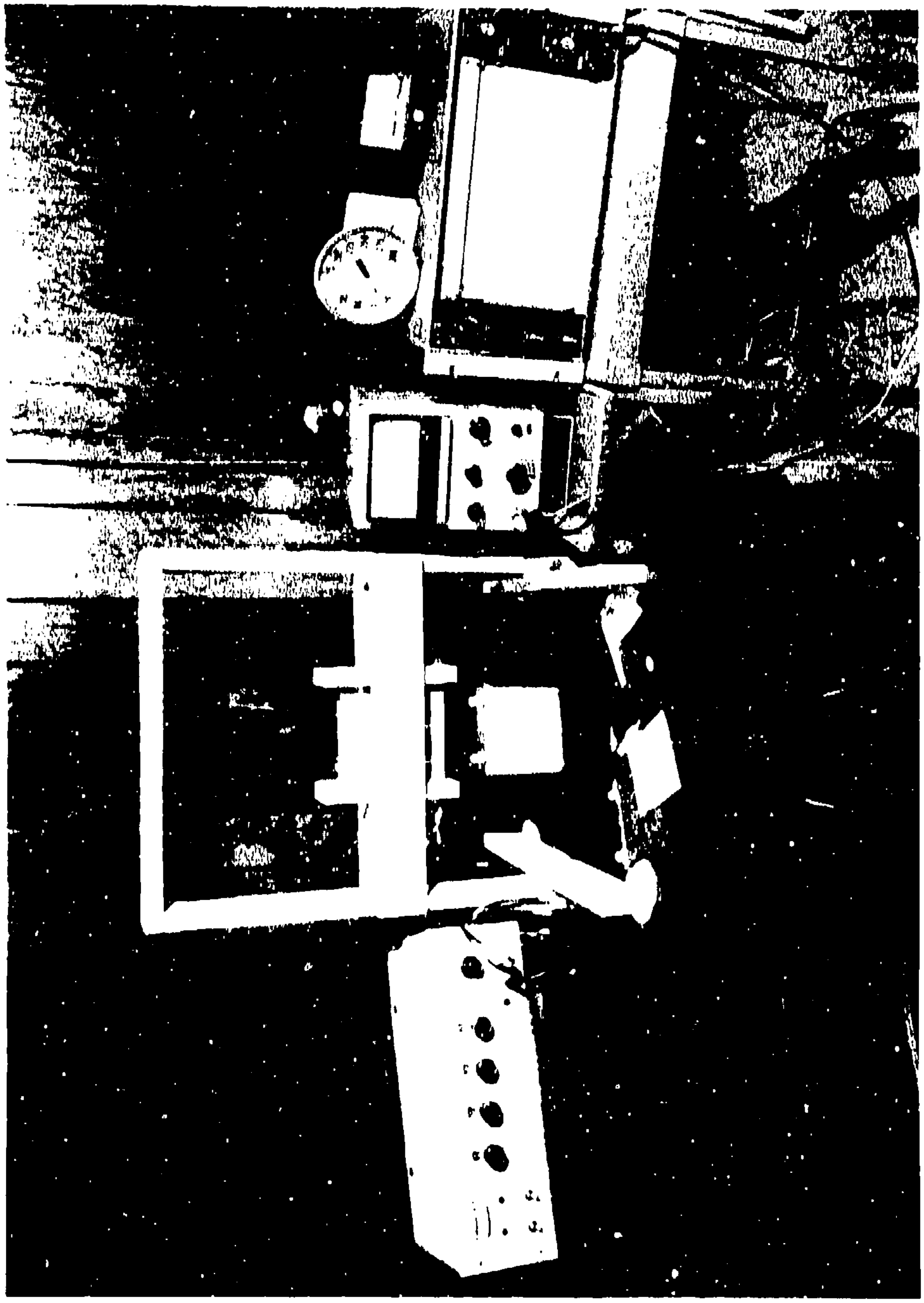


Figure 1. Experimental set-up.

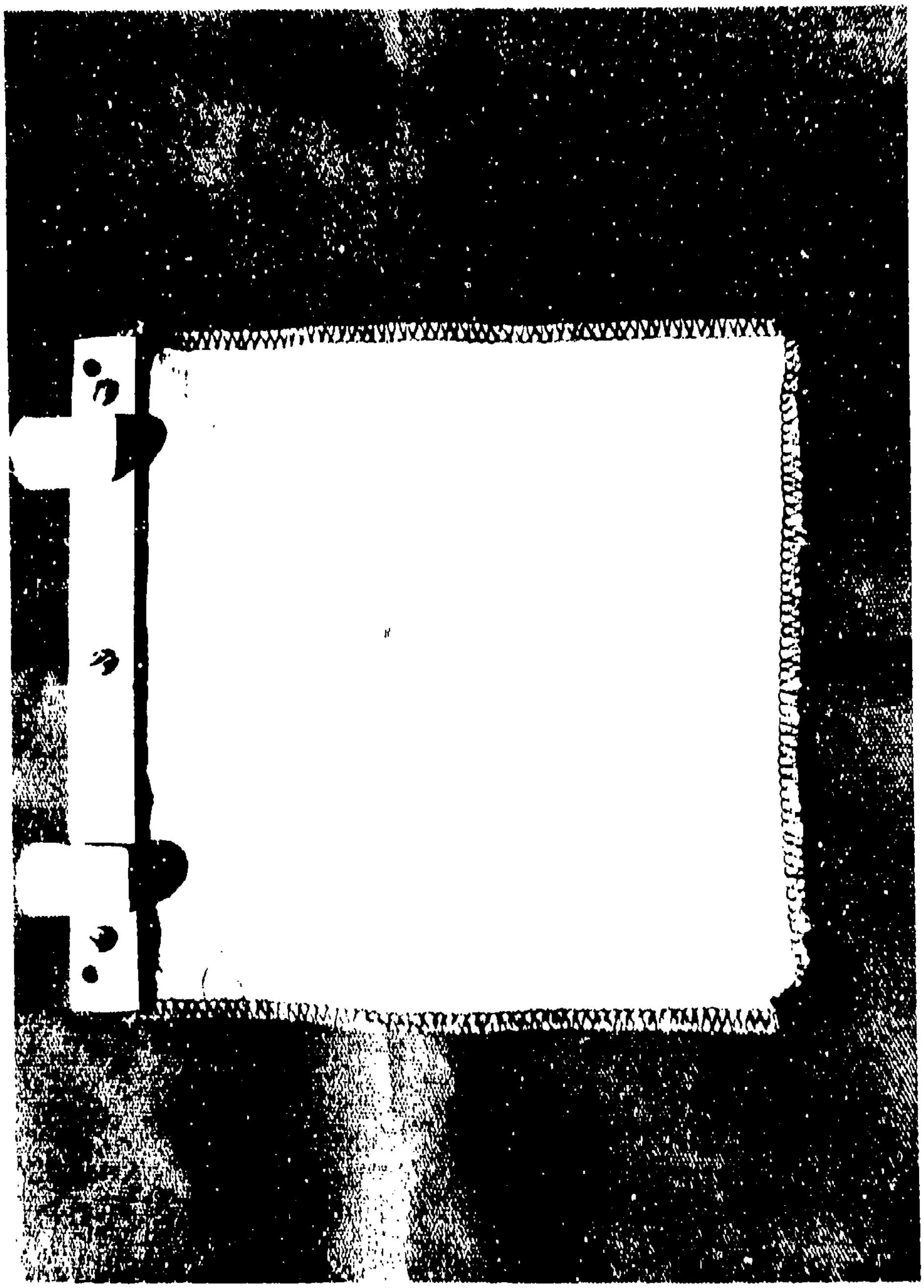


Figure 2. Six-inch square cloth sample in holder.

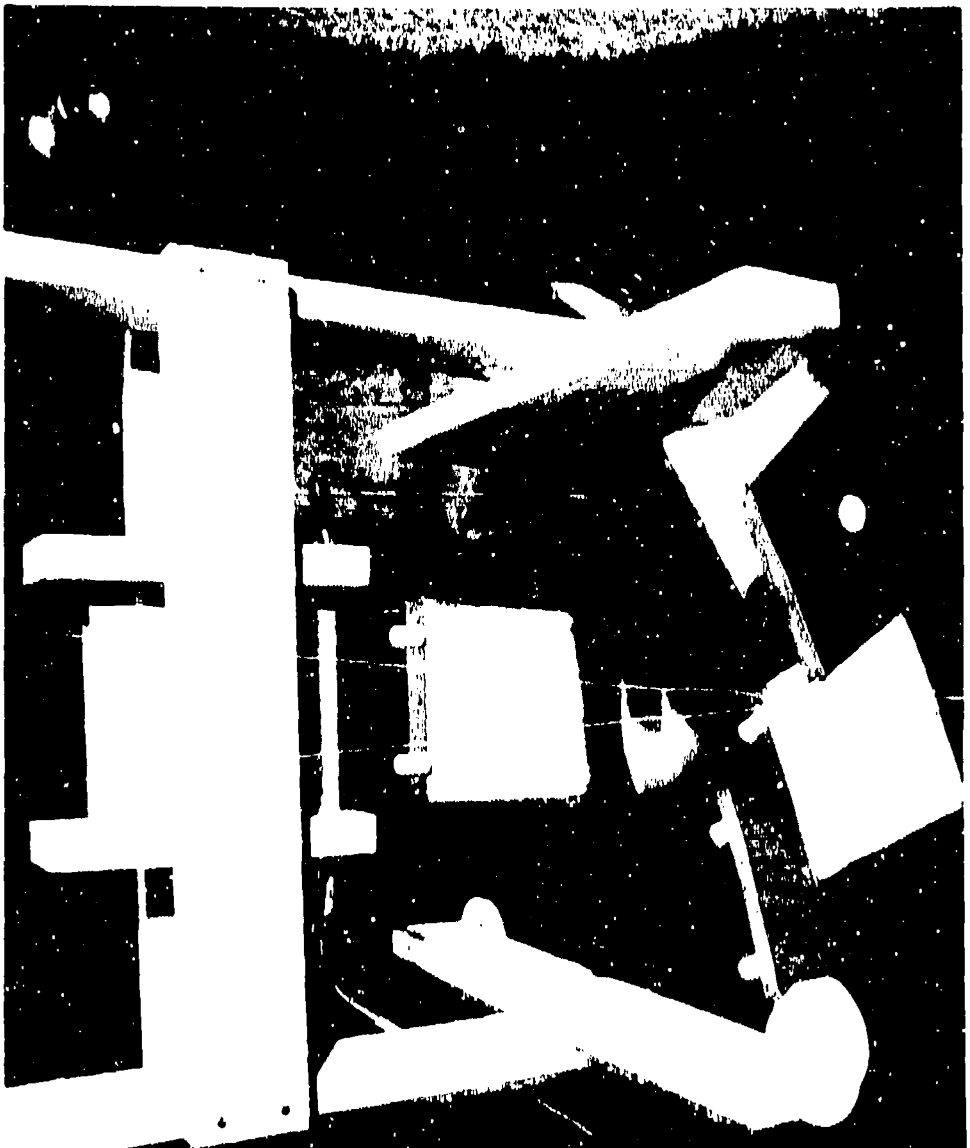


Figure 3. Cloth sample exiting charging plates and entering Faraday cup.

Top View

Front View

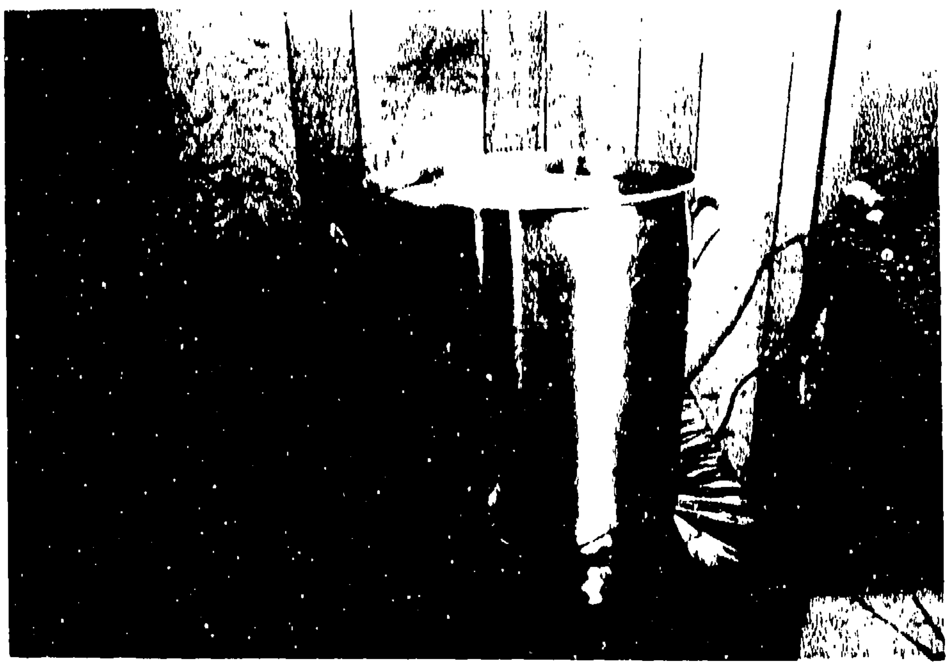


Figure 4. Faraday cup.

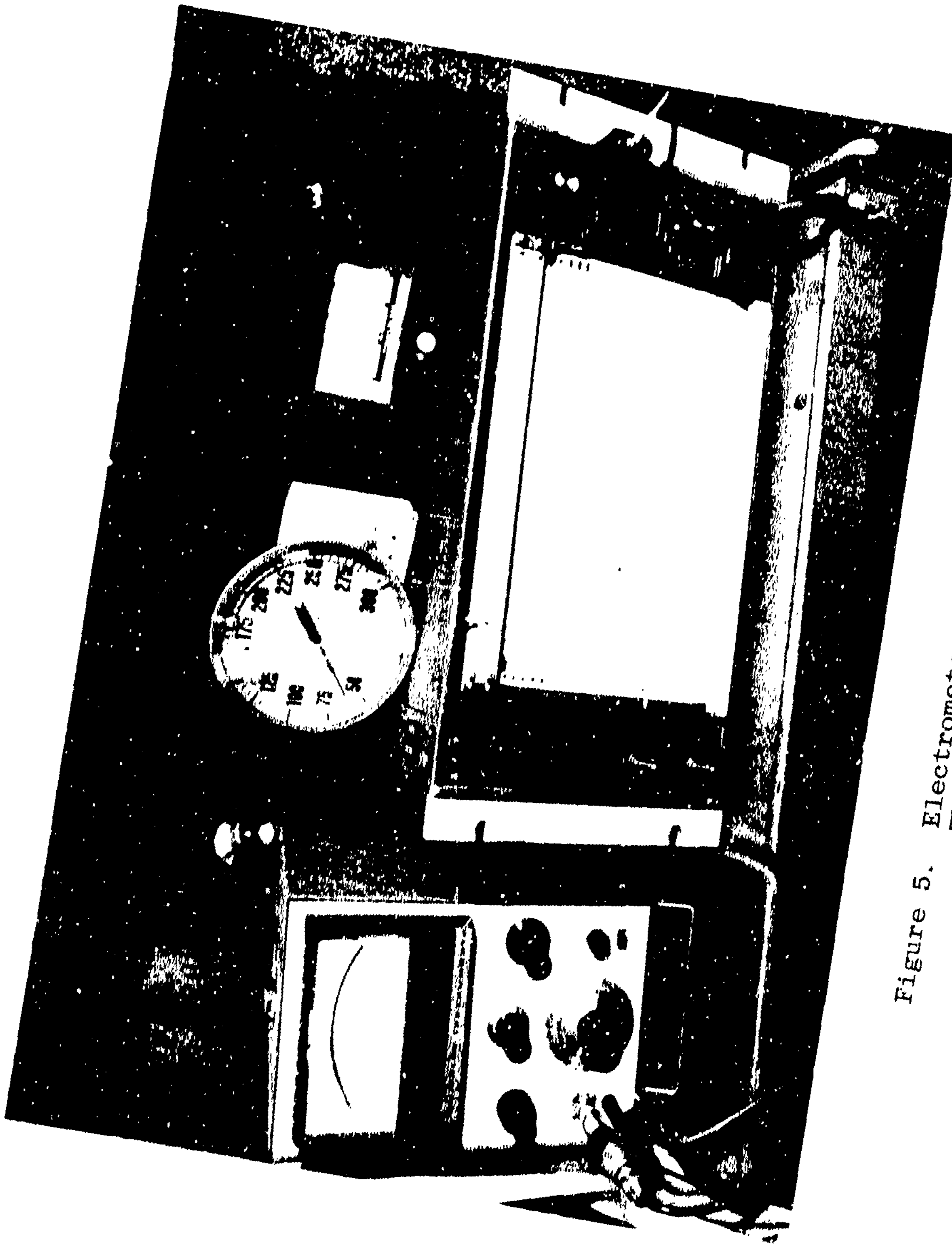


Figure 5. Electrometer, recorder,
Thermometer and hygrometer.

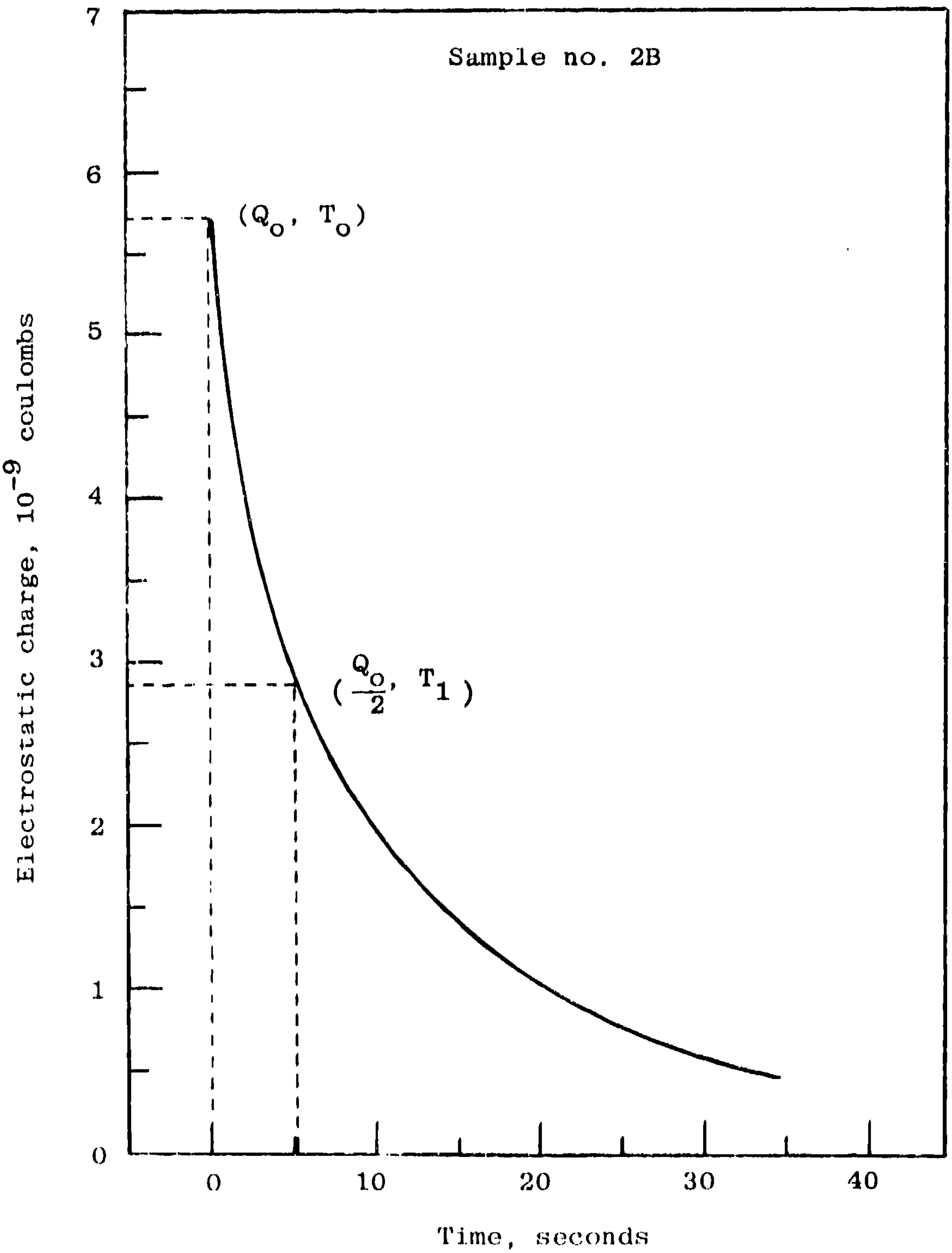


Figure 6. Charge vs. time trace, unlaundered fabric.

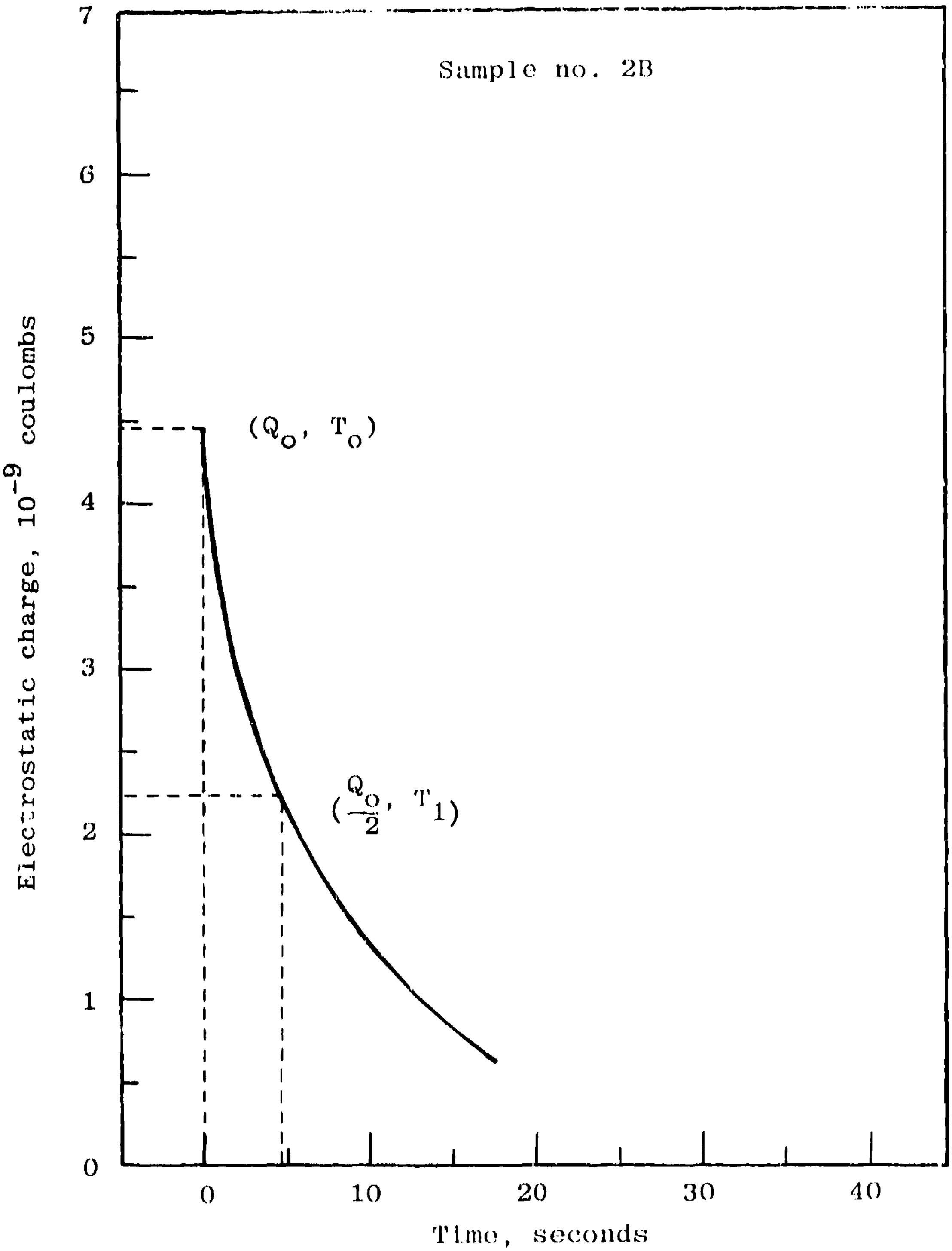


Figure 7. Charge vs. time trace, laundered fabric.

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